Design and Evaluation of Techniques to Improve User Comfort During Prolonged Use of Virtual Reality

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Design and Evaluation of Techniques to Improve User Comfort During Prolonged Use of Virtual Reality

by
Kien Tran Pham Thai

Abstract

Virtual Reality (VR) has become a consumer technology, and as such has spread to include many different applications at work, home, school and play, for multiple kinds of users. However, using conventional immersive head-mounted displays (HMD) can lead to degradation in health, such as physical and mental fatigue and motion sickness. It also creates difficulties in interacting with objects and people in the physical world: immersed users cannot easily locate objects around them (e.g., keyboard, mouse, smartphone), or have meaningful face-to-face conversations with people.

This thesis addresses these issues from both the "comfort" side and the "real-world interaction" side. We propose (1) A novel immersive health-recovery technique called "Active Breaks", (2) a means of dynamically controlling how much of the real world the immersed user can see, and (3) techniques for a non-immersed user to better socially connect with an immersed user. The systems described here are built around a unified framework ("Workspace VR"), that brings together existing and novel technologies for visual and audio cues to support real-world interactions (nearby objects, people) for the VR user, and face-to-face communication for the non-VR user. Using these solutions we present encouraging evidence in terms of implementation and improvements: Regarding Active Breaks, our users highly preferred both real-word-based and VR-based version, although the VR-based eye exercises used in this version had some drawbacks. Regarding systems, our combination of the visual channels resulted in a much larger field of view for the VR user to interact with the physical world. Initial investigations into our first HMD prototype showed that each channel provided accurate view areas (peripheral and central vision) for the user to interact with nearby objects in different task scenarios, received high user preference, potentially maintained a high level of immersion, and did not induce any significant VR sickness. In the latest version, we optimized the involved technologies, added more features that also support the non-VR user (audio channel, eye contact cues), designed a new HMD in a scalable fashion, and planned a face-to-face user study to evaluate the impact of the new system as a whole.

Dedication

During my PhD at the HIT Lab NZ and University of Canterbury, I have received a ton of help from people around me.

This is to send my great appreciation to Prof. Robert W. Lindeman for accepting and supporting me to be a HIT Lab NZ member long before my arrival. He managed to offer the best possible option to support my study at the lab as well as with my coming to NZ. He also introduced me to this interesting topic and believed in my capability. He always encouraged us to keep a balance between producing good research works as well as appreciating the beauty of NZ, and it always seemed that the difficulties in my PhD journey eased away after coming to discuss them with him. This also taught me about being calm and looking for the simplicity of the solution.

I want to say a big thank to Dr. Sungchul Jung for his guidance and inspiration toward my work with valuable advice and tremendous support. I admire his mentorship as being among the best teachers I have known so far. I also thank him for his understanding, sympathy and patience with me even though sometimes I found myself quite stubborn.

I would like to send many thanks to the staff and my labmates Ken, Jackie, Mel, Bhuvan, Jason, Alaeddin, Humayun, Nikita and Kris Tong (especially for helping me with artistic illustrations of the thesis), for their care, friendliness, and support even before my arrival at the HIT Lab NZ, and for making my three-year-PhD here to become a rewarding and joyful journey.

Last but not least, I want to send all the best to all of my family members: my wife, my mom and dad, my younger sisters and their families: my mother-father-younger brother in law, for always being by my side and giving endless encouragement throughout the years of the work.

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Date: September 30, 2020

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Chapter 1

Introduction

1.1 Motivation

Looking into the future, Jens Grubert et al. pointed out that "We envision the future office worker to be able to work productively everywhere, solely using portable standard input devices and immersive head-mounted displays. Virtual reality (VR) has the potential to enable this, by allowing users to create working environments of their choice and by relieving them from physical world limitations such as constrained space or noisy environments" [44]. Indeed, this VR technology has brought us the 3D computer-generated environments now widely used in spatial simulation, data visualization, and gaming or entertainment. More, the technology can offer the virtual re-creation of our world or even build up totally new fantasy worlds [184]. In terms of spatial environments, users can run VR at their workstations while seated, or can expand the usage to room-based installations to experience more movement freedom within a specific boundary. The user wears a head-mounted display (HMD) to access the virtual environment (VE) and to be enclosed visually and audibly, and can even experience more sensory channels.

In practice, the first fundamental issue is the health of a user working with VR, because the technology induces side effects broadly known as VR sickness [25,

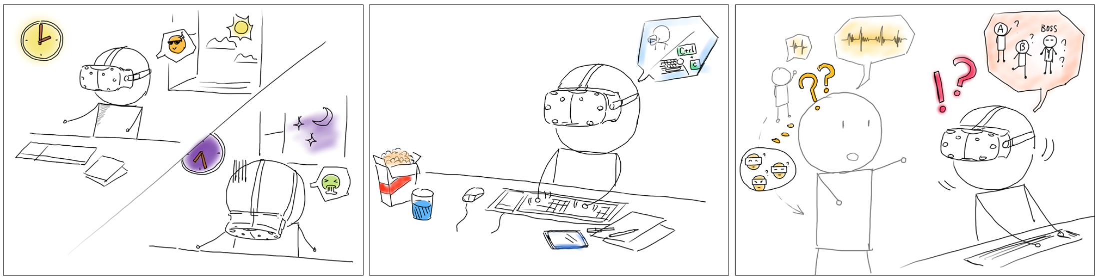

Figure 1.1: A VR user may experience a feeling of sickness (left), difficulties in using devices/items in the real-world (middle), and limitations in having a conversation with others. Non-VR users also have difficulties in engaging the VR user in conversation (right).

105, 133, 143, 169], (see Fig.1.1, left). VR sickness is the term that covers all health problems (from general to specific) that may affect a user during a VR session [46]. These include motion sickness (real apparent motion), which includes both cybersickness (induced motion sickness) and simulator sickness (shortcomings of the simulator, rather than the actual simulated situation), and other forms of sickness such as fatigue and discomfort. Those issues progress through four different stages: severity increase during initial exposure; adaptation over time, with illness subsiding; aftereffects; and time-consuming re-adaptation when re-entering the real world [21]. One major contributor to VR sicknesses is visual fatigue (VF) [7, 47, 53, 56, 61, 87, 118, 153, 154, 169]. Visual fatigue is mainly caused by the influence of a conventional HMD's optic settings and displays, which cause eyestrain, tiredness, and difficulty to adapt at the beginning and re-adapt to the real world afterwards. Slow re-adaptation to the real world also has health and safety implications, such as driving too soon after a session. Although this is an active area of research, existing solutions focus on inventing hardware and software modifications; the use of clinical eye exercises with their efficiency, simplicity, and naturalness has not yet been explored.

Secondly, VR HMDs are currently designed to block outside interruptions as much as possible to focus on providing the best sense of presence. In practical usage, this results in difficulties with interacting with physical world items (see Fig. 1.1, middle) such as input devices (keyboard, mouse), a smartphone for maintaining social connections, and any other item a user might wish to access such as water cups, notepaper, or even a popcorn bucket [19, 41, 44, 106, 178]. In a collaborative environment, the HMD-wearing participant will also experience difficulties with other people coming in for a conversation or with monitoring the ambient environment (see Fig. 1.1, right) [33, 41, 55, 58, 62, 65, 74, 115, 140, 165]. In terms of providing visual experiences, one well-known approach uses Video-See-Through (VST) technology to capture the real world using cameras [18, 19, 32, 106, 138], while another early prototype used Dynamic Immersion technology to let in the physical world using transparent LCD panels [94]. In return, the non-VR user will experience difficulty in getting into a conversation with a face-blocked VR colleague without regular communication cues or a sense of engagement in the talk [22, 43, 45, 102]. These experiences confirm that real-world (RW) connection is as vital as having an immersive and continuous VR experience, because people cannot fully engage from both worlds (VR and RW), and any sudden switching will break their experience as well as cause more discomfort.

Thus, there is a demand for providing the VR user with the capability of maintaining a high level of health and well-being throughout their working day and the ease of obtaining ambient information and interactions (via visual and audio channels) with their workplace. Further, in a collaborative office environment, the VR user also has connections with Non-VR users, and these connections are bi-directional, and so these also need solutions. We propose new solutions/techniques offering both effectiveness and simplicity, then unify those into new HMD designs and systems after a study into the existing work in this area. In employing these solutions, VR users can have a continuous workflow within the VR environment as well as perform efficient health recovery techniques, and interact with their physical world easily, conveniently, and naturally. Lastly, we report on user studies to investigate the impact of the new techniques/devices in terms of usability and to obtain insights for future enhancements. All of this is motivated by the need to allow people to spend large amounts of productive time in VR, especially in office environments.

1.2 Research Questions

Based on the demands outlined in the previous section regarding prolonged VR experiences, we identify three research questions below:

- **RQ1**: How can we provide the VR user with a healthy experience? We focus on Visual Fatigue to introduce new techniques with effectiveness, rapid recovery, simplicity and naturalness. Thus, the user can apply them in different phases of their VR experience, e.g., during breaks or before returning to the RW.
- **RQ2**: How can we ease RW interactions for VR users (including nearby objects)? We aim for solutions that are effective and natural in helping the user to interact easily with the RW without having to take the HMD off. We also look at enhancing the smoothness of transitioning between the RW and VR, in order to keep the comfort levels high.
- **RQ3**: How can we facilitate face-to-face conversations between VR and non-VR users? We focus on both sides of a conversation between a VR and a non-VR user in a collaborative environment. Here, the VR user needs sufficient visual and audio cues, and the non-VR user demands a certain amount of communication cues, such as eye contact.

1.3 Thesis Structure

To address the research questions, the thesis starts by providing a solid exploration of the existing state of the art in relevant VR research areas and reveals research gaps (Chapter 2). Then, we investigate newly proposed techniques and solutions (Chapters 3, 4, 5), including the sub-problem spaces, apparatus/techniques, user study design and procedures, and data analysis in each published work. Lastly, Chapter 6 gives conclusions, summarizes the contributions and outlines future work.

Chapter 2

Literature Review

This chapter starts with a general understanding of VR technology, its counterparts, and input/output devices, then goes deeper into VR-related problems and existing solutions in exploiting VR in long-term usage for an office environment. In the office, there is a need for quick and efficient health-recovery techniques, and demand for the capability of perceiving and interacting with nearby physical items. In addition, there is a need to support having effective face-to-face connection between the VR and non-VR users.

2.1 Virtual Reality Technology

2.1.1 Input/Output

VR is a member of the virtual technology family (see Fig. 2.1) [112]. The Reality-Virtuality continuum has at one end the RW that is known to us, and VR at the other, where the RW is entirely replaced by a surrounding virtual construction. Between these two ends, there is Mixed Reality (MR) technology which has two sub-technologies of Augmented Reality (AR) and Augmented Virtuality (AV), where the RW is captured and overlaid with either 2D layers of extra information or 3D objects. VR is suitable for simulations of spaces which can be known or unknown, employing completely different

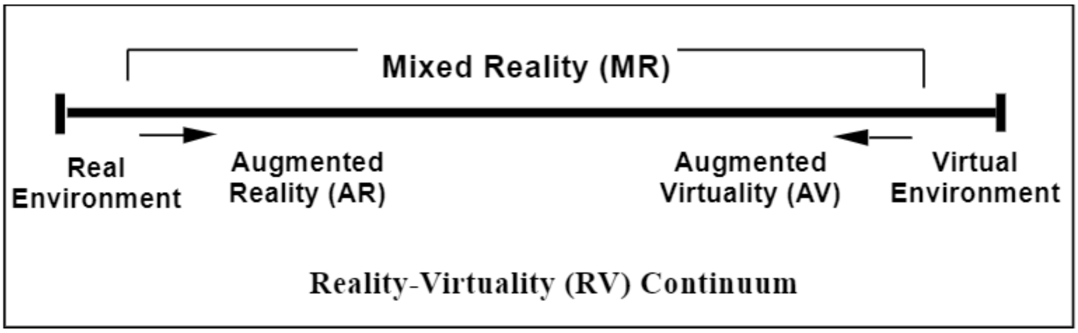

Figure 2.1: Virtual Reality creates the most immersive experience compared to other technologies in the family that alter our perception of the known world [112].

sensory laws suitable for complex data visualization, gaming, and entertainment [184]. Skarbez and colleagues mentioned additional applications of VR in psychological research and treatment, military and medical training, and sociological research [158]. To enter such virtual environments, in addition to visual (VR headset or HMD) [15, 125] and audio [95, 96, 101, 111] cues, haptic, olfactory, and gustatory [36, 72] devices are also available to render virtual content to the user through their sensory channels and equipment (joystick [14], keyboard [13, 16, 17, 174], and mouse [39, 174, 175]).

2.1.2 Immersive Systems for the Sense of Presence

The concept of *immersion* is an objective characteristic of a VE system [159] or a set of valid actions supported by a VE system [160]. When the VR provides a continuous stream of stimuli and experience [187], this leads to logical immersion [98]. *Presence* is sometimes synonymous with immersion [158], but it also has spatial understanding and peripheral awareness [16]. Thus, a higher sense of presence may indicate that a system is more immersive [158].

The sense of presence is defined as "being there" in a VE [2, 6, 26, 28, 48, 51, 59, 91, 99, 108, 109, 149, 157, 158, 162, 183, 186, 187]. The sense of presence focuses on the VR user experience and includes subjective personal presence, social presence, and environmental presence [51]. Presence has the distinct advantage of being a metric applicable to any VE. Thus, by presenting different VEs to a single user to compare and report, the researcher can obtain insights towards their design [158]. Presence is an important feature of a VR system [91, 149], but the concept may vary based on the application contexts, especially on the environments where there is a need for RW information.

Measures

Research into effective measures of presence can be divided into two major groups of objective and subjective measures.

Subjective Measures are the form in which users report their experience to the researcher. As shown in Table 2.1, we identified 14 questionnaires in this category, dating back to 1994, when Slater et al. proposed the first questionnaire to measure the sense of presence, the Slater-Usoh-Steed (SUS) questionnaire [162]. The SUS is one of the most widely used questionnaires, and has six questions. The Presence Questionnaire (PQ) for VR was introduced in 1998 by Witmer and Singer [187]. This questionnaire covers four factors, Control, Sensory, Distraction and Realism, distributed across 19 questions. In the same paper, the authors also presented the Immersive Tendencies Questionnaire (ITQ) for VR [187]. This questionnaire contains 18 questions and measures an individual's tendency to become involved in everyday activities as a proxy for their likelihood to experience presence in a VE.

The Igroup Presence Questionnaire (IPQ) for VR was proposed by Schubert et al. [149], and has 14 items with four sub-scales, Presence, Spatial Presence, Involvement, and Realness for measuring not only VR but also other media. Vorderer et al. presented the MEC Spatial Presence Questionnaire (MEC-SPQ) for cross-media [183]. This questionnaire focuses on the spatial side of a given VE. It has nine constructions that span across four process factors (Attention Allocation, Spatial Situation Model, Spatial Presence—self-location, and Spatial Presence—possible actions), two psychological state factors (Higher Cognitive Involvement and Suspension of Disbelief), and three psychological trait factors (Domain-specific Interest, Visual/Spatial Imagery, and

Absorption). There are three versions of the MEC-SPQ, Long with 72 items, Medium with 54 items, and Short with 36 items. The ITC Sense of Presence Inventory (ITC-SOPI) for cross-media [91] is a 44-item questionnaire that focuses on users' experiences with different media types, including TV and movies. It has four constructions of the questions, Sense of Physical Space, Engagement, Naturalness, and Negative Effects.

The IPO Social Questionnaire (IPO-SPQ) for telecom applications [26] is a 17-item questionnaire used in the cross-media application area. This questionnaire focuses on the determinant of social presence in video conferencing, measuring two parts of Osgood's semantic differential technique and subjective attitude statements on a 7-point "agree" to "disagree" Likert-based scale. However, no full version of items for this questionnaire could be found. The Temple Presence Inventory (TPI) for cross-media questionnaire has 42 items [99], and assesses five dimensions of presence, Transportation, Immersion, Realism, Social Actor Within a Medium, and Social Richness. The Behavior Presence in Threatening VEs (BPTT) for VR [103] questionnaire contains 32 items to assess five different virtual environments of house, canyon, fire, trucks/trains, and sharks. For each environment there are different numbers of questions for evaluating specific behaviours of stereotyped body movements such as attitude and gestures, and more complex sequences such as escaping from incoming danger or focusing on aural cues or strategies of self-preservation.

Baños and her colleagues presented a 77-item questionnaire, the Reality Judgment and Presence Questionnaire (RJPQ) for VR [8]. The authors intended to measure nine factors of experience including reality judgment, presence, emotional involvement, interaction, control, attention/flow, realism, congruence/continuity, and expectations. The Bouchard et al. questionnaire for VR is a single question "To what extent do you feel present in the virtual environment as if you were really there?" as a measure of presence, [12]. Takatalo and colleagues developed the Experimental Virtual Environment Experience Questionnaire (EVEQ) for VR [172]. The EVEQ consists of 124 questions with 19 sub-scales. Chertoff and colleagues presented the Virtual Experience Test (VET) for cross-media [23]. This survey includes 17 questions addressing five dimensions of experiential design, Effective, Cognitive, Sensory (immersion), Active

Table 2.1: The most frequently used presence questionnaires.

Questionnaire	**Description**	**Source**	**Application**
Slater Usoh Steed Presence Questionnaire (SUS)	6 items	[149, 162, 169]	VR
Presence Questionnaire (PQ)	19 items	[103, 128, 151, 186, 187]	VR
Immersive Tendency Questionnaire (ITQ)	18 items	[151, 187]	VR
Igroup Presence Questionnaire (IPQ)	14 items	[103, 106, 149, 186]	VR
MEC Spatial Presence Questionnaire (MEC_SPQ)	3 versions	[149, 183]	Cross Media
ITC Sense of Presence Inventory (ITC-SOPI)	44 items	[91, 103, 149, 186]	Cross Media
IPO Social Questionnaire (IPO-SPQ)	17 items	[26, 149]	Telecom
Temple Presence Inventory (TPI)	42 items	[99, 106, 149]	Cross Media
Virtual Reality Symptom Questionnaire (VRSQ)	9 items	[2, 78]	VR
Behavior Presence in Threatening VEs (BPTT)	32 items	[103]	VR
Reality Judgment and Presence Questionnaire (RJPQ)	77 items	[8]	VR
Bouchard et al. questionnaire	1 item	[12]	VR
Experimental Virtual Environment-Experience Questionnaire (EVEQ)	124 items	[172]	VR
Virtual Experience Test (VET)	17 items	[23]	Cross Media

("personal connection...to an experience"), and Relational (social).

Each of these questionnaires covers different categories (VR focus, cross-media) with variations in lengths and application specifications. Regarding the assessment of presence, the IPQ seems to be appropriate for a mixed-mode experience, where there are items to assess the presence level in both VR and potentially-injected RW elements for the user experience.

Objective Measures are the use of devices, sensors, and other equipment to capture data from the user objectively. These consist of three major groups of psycho-physiological, neural, and behavioural measures, and are carried out along with task performance assessments.

Psycho-physiological measures include cardiovascular, blood pressure, skin, ocular, pupillometry, and facial measures. The cardiovascular measurements of blood pressure and heart rate (electrocardiogram (ECG)) are used to indicate the attention in presence [80]: the heart rate to measure automatic attention, and a measurement of the influence of breathing on heart rate to assess controlled attention [80]. There is general agreement that cardiovascular activities correlate with emotional experience, hedonic valence, orienting response to novelty, and defensive response [28, 59, 108]. Ravaja et al., for example, considered cardiovascular activity to be an indicator of valence and arousal, attention, cognitive effort, stress, and orientation [131]. However, notwithstanding this general agreement, cardiovascular measurements are difficult to generalise due to variations in human-body characteristics, and the interpretation of those data either in real-time or offline is challenging [158]. Skin measurements include temperature and conductance metrics and show emotional arousal, memory effects, and reorienting response to novelty [28, 80, 108]. Ocular measures require the use of spatial (amplitude of saccades and scan-path length) and temporal (fixation duration, fixation number, scan-path duration) eye-tracking techniques [42], while pupillometry measures are relevant to how pupils react to different stimuli. Both of these methods indicate involuntary behaviours of the eyes (not controlled by the brain), which is useful to capture the response to stimuli and emotions for presence [59]. Facial electromyography (EMG) is the measurement of the emotional response of the user in a VE [59, 80]. This facial assessment uses surface-attached electrodes placed on the skin of the face to capture potential differences. According to Mehan and colleagues, skin conductance measures are less sensitive, less powerful, and slower to respond than heart-rate capture [46, 108]. Also, these sensors take time to deploy, remove, and warm-up, and afford less reliable data and less immersion due to the presence of wiring and mounting devices as well as limiting the user's movements [103].

Neural Measures include electroencephalogram (EEG) and Functional Magnetic Resonance Imaging (fMRI). EEG is the capture of brain signals and indicate the level of presence from a cognitive [28,80,129,171] or emotional [59] perspective. EEG equipment can amplify and record electrical activity using temporarily-adhered electrodes on the scalp. Schlogl et al. discussed the properties, advantages, and disadvantages of EEG [146]. According to the authors, the use of EEG is non-invasive, has a high time-resolution, and is usable in almost any environment. However, the method may have a poor signal-to-noise ratio and inter- and intra-trial variability. An fMRI device is a special device that can detect changes in blood flow in the brain using magnetic fields. This behaviour indicates the cognitive effort from activated areas in the brain from a VR experience. Thus, brain activity patterns associated with various types of mental activities can be studied [54]. However, fMRI devices are large and are very susceptible to metal in the area of capture.

2.1.3 Summary

The section started with an overview of the VR technology input/output devices. We then gave a definition of an immersive system as an objective tool for producing the subjective sense of presence in users. The section also probed further into the concept, relevant factors and measures of presence. In the next section, we will study the first problems when considering the use of VR over an extended period, which are VR sickness and visual fatigue.

2.2 Major Detriments to Long-term VR Use

Steinicke et al. [169] were one of the first groups to report on long-term exposure to VR, covering a day-long VR experience. The subject wore an HMD for 24 hours in blocks of two hours with 10-minute breaks in between. The experiment included different VE scenarios (island beach, living space), and activities such as idle, work, rest, diet, and entertainment. The user/researcher experienced health degradation (feeling sick, experiencing visual problems, and feeling a sense of heaviness), and also felt confusion between the two worlds after prolonged use.

2.2.1 VR Sickness

Health concerns have been an active research topic for VR. Cybersickness is recognised as motion-induced sickness in discussions on VR-related health issues [143]. According to Rebenitsch et al., cybersickness is poli-symptomatic (many symptoms including general health and visual fatigue problems) and polygenic (symptoms manifestations differ from individual to individual), making it a complicated illness to understand and describe [133]. Davis and colleagues distinguished cybersickness from motion sickness (real apparent motion), as cybersickness is a subset of motion sickness involving moving in VR with a stationary manner of user position [25]. This phenomenon is also called "self-motion", "vection" [105], or "visual induced motion sickness" [133]. Cybersickness also differs from simulator sickness, which arises when there are discrepancies between actual movements and simulator movements [25].

Cybersickness has different effects depending on the length of exposure, and is only a subset of the VR related-problems. Rebenitsch et al. [133], Kennedy et al. [77] and Champney et al. [21] agreed that the longer a user is exposed to a VE, the higher number of initial symptoms and the greater their severity, with Kennedy et al. confirming that this negative influence diminishes with the number of repetitions, since the body seems to adapt to the new visual setup [77]. Later on, Champney et al. added two more chronic consequences on the user, the aftereffects after they finish a VR session, and difficulties in adapting back into the physical world (prism theory in researching glasses and goggles) [21]. The authors were also concerned that the time for recovery from cybersickness may be longer than the VR duration itself. Lately, Guna et al. used the term "VR sickness" to cover cybersickness, simulator sickness, and other forms of related sicknesses, fatigue, and discomfort caused by VR activity [46].

Factors and Theories of VR Sickness

The factors of the various aspects of VR sickness cover two main categories of human and technological factors (see Table 2.2) [77, 89].

Table 2.2: There are a number of factors that influence whether the VR user may experience VR sickness and how severe it can be.

Human Factors	**Technological Factors**
Gender	FOV
Age	Positioning
Adaptation	Delays
Experience, and exposure duration	Flicker
History of motion sickness	Calibration, ergonomics, controls
Illness, sleep, fatigue, drugs	Tracking
BMI, weight, height	

Human factors include gender, age, adaptation, experienced exposure duration, history of motion sickness, illness/drug/sleep/fatigue, and Body Mass Index (BMI) attributes. Because women have a greater field of view, they are more sensitive to flicker from their peripheral visual system. There is also evidence that female subjects have some hormone interference [25, 64, 81, 89, 113, 132, 133]. Concerning age, the level of susceptibility to sickness gradually increases from 2 to 12 years, and from to 12 to 21 years. People beyond these ages become more prone to VR sickness [25, 64, 81, 89, 113, 132]. Adaptation is the phenomenon earlier found in military simulator systems where more prior hours to the simulator systems resulted in fewer sickness symptoms [64, 133]. When considering this experience ([7, 25, 64, 77, 81, 83, 89, 132, 133]), the more time subjects stayed within a VR system, the less sickness symptoms presented [64], and total sickness subsided over repeated exposure [25]. If a subject had a previous history of experiencing motion sickness, this correlated with the experienced cybersickness level (found in a helicopter military simulator) [64, 133]. Furthermore, if the body of the user was not in good condition (for example ill, sleepy, fatigued, or affected by drugs), the subject was more likely to experience sickness [25, 64, 81, 89]. While investigating the contribution of BMI factors, it seems that taller subjects had fewer symptoms [132].

Technological factors include Field of View (FOV), positioning, delays, flicker, calibration/ergonomics/controls, and tracking while using an HMD. In general, an HMD has a limited FOV, smaller than the viewing angle of human eyes. Increasing the FOV will provide more realism, but this gain in FOV also correlates with an increase in cybersickness severity [6,38,133,151]. Positioning is another factor, where a good sitting posture may result in a lower level of sickness than a standing position [25, 81, 89]. Delays are the amount of noticeable time from a user action to the time of system reaction, and contribute to the buildup of discomfort for the user [6,25,34,89,121]. Flicker is the state where the peripheral vision of the eyes is more sensitive to display frequency, which is different among subjects and has a correlation with the FOV [25,81]. Thus, low display frequency is easily detected by the visual system and causes more sickness. Poor calibration for interpupillary distance (or IPD), a heavy HMD, or poor-fitting HMD can result in discomfort, restrict the freedom of movement, and distract the users from being immersed in the VE [25]. If the users have more control over the environment this will make the VE more realistic, but the expressiveness of controls is still limited in conventional VR applications [25]. The last problem is tracking latency; a noticeable difference between the moment of movement change and the corresponding view in VR change will cause an unpleasant experience [89,113].

Explaining the sources of sickness is an active research field with many proposals for the origins, including Postural Instability theory [25,64,81,89,133,134,139], Poison theory [25, 89, 133], Rest-frame (wrong gravitational sensory vs. the VR) theory [133], Evolution theory [179], and (Re)Adaptation (when entering the VE and before coming back to the everyday world) [21, 133]. However, the oldest and most accepted explanation for the source is Sensory Conflict theory [6, 25, 38, 75, 76, 76, 81, 89, 122, 133, 134, 139, 179]. This theory is based on a proposition that discrepancies between the senses which provide information about the body's orientation and motion cause a perceptual conflict which the body does not know how to handle. With cybersickness and motion sickness, the two primary senses that are involved are the vestibular sense and the visual sense. These sensory conflicts arise when the sensory information is not the stimulus that the subject expects, based on his/her experience.

Table 2.3: To examine the presence of VR sickness, there is a wide range of detectable symptoms [25, 31, 64, 75, 75, 78, 86, 89, 116, 133, 167, 182].

Symptom/Sign	**Symptom/Sign**
Nausea	Blurred vision
Vertigo	Headache
Pale skin	Stomach awareness, full stomach
Postural disequilibrium	Increased salivation
Cold sweat/sweating	Burping
Sopite syndrome (extreme drowsiness)	Fatigue
Vomiting, queasy	Afraid
Difficulty focusing	Eyestrain/oculomotor changes/Asthenopia
Dizziness	Dry mouth
Full head	General discomfort
Disorientation	

Symptoms and Measures

In terms of symptoms, a subject who has VR sickness may have several symptoms (see Table 2.3). Those symptoms can reside in a particular human organ or appear as general inconvenient feelings [25, 31, 64, 75, 75, 86, 89, 116, 133, 167, 182].

Instruments for collecting subjective data for VR sickness include several questionnaires, the Simulator Sickness Questionnaire (SSQ), Nausea Profile (NP), Subjective Units of Distress Scale (SUDS), and Virtual Reality Symptom Questionnaire (VRSQ). The SSQ contains 16 items with Likert-based answers ranging from none, slight, moderate, to severe symptoms [143] and was developed from the Motion Sickness History Questionnaire [166, 182]. Rebenitsch et al. interpreted the SSQ score and classified the score behaviours into different assessing environments including military simulator, seasickness, space sickness, and cybersickness [133]. With cybersickness or VR sickness, the SSQ questionnaire shows the score of Disorientation higher than Nausea, followed by Oculomotor [133, 169]. The NP is a 17-item questionnaire and used to measure complex experiences related to nausea. Each item has a 10-point ranking from 0 to 9 which refers to "not at all" to "severely" [116]. The SUDS is a single scaling question to assess the level of stress starting from "No distress" to "Extreme distress" with a visual analog scale for the subject to use [11]. The VRSQ for VR [78] contains nine items including general discomfort, fatigue, eyestrain, difficulty focusing, headache, fullness of head, blurred vision, dizziness, and vertigo. These items are categorized into two components of Oculomotor (the first four symptoms) and Disorientation (the remaining five items).

Objective measures for VR sickness include behavioural and psycho-physiological measures. *Behavioural measures* use three methods. First, the postural stability test is to assess ataxia (body axes) as a sign of experiencing simulator sickness [31, 64, 81, 133, 182]. A user is required to do two tests of standing on the preferred leg and standing on the non-preferred leg. The researcher checks whether the person stands without sidestepping, losing balance or deviating from the position for 30 seconds. The test can happen at both the beginning and the end of a VR session. Second, facial pallor can be captured with a camera to examine the severity of sickness [64]. Third, the eye blink rate is also an indicator, where any increasing or decreasing of the rate compared from an average pace is a sign of an abnormality [25].

Psycho-physiological measures use similar methods with the assessing of the presence level (see section 2.1.2) as well as other approaches. Similar to presence detection, researchers use psycho-physiological and neural methods including electrocardiogram (ECG), blood pressure testing [25, 46, 103, 109, 133, 188], skin measures [46, 64, 103, 109], and a neural measures of EEG [25]. Additionally, there are also new measures of gastric effects with an electrogastrogram to detect stomach behaviour [25,64,133], and respiration measures [64] for breathing patterns to capture the body's reaction to certain stimuli.

Solutions

The solutions for VR sickness include software, hardware, simple breaks, and games or activities. In terms of software, there are different solutions proposed for dealing with the issue. First, Independent Visual Background (IVB) is the application of a visual-software-stationary-grid on the virtual scene for providing a cue of fixation in motion VR environments [30, 31, 89, 133]. According to Rebenitsch and Owen, the

IVB contributes to a reduction of VR sickness compared to a non-IVB environment, with a lower SSQ total score [133]. In a different implementation, Duh et al. used IVB for a screen-based environment with 3D shutter glasses. The authors confirmed the reduction of balance disturbance for the IVB versus a non-IVB environment [30, 31]. The implementation of IVB is also called a "rest-frame" and has been shown to work on a low-end, low-FOV HMD with simple visual stimulation [89]. Second, Fernandes et al. proposed the use of dynamic changes of the FOV to reduce sicknesses [38]. The FOV is adjusted on the fly to lower the vection influence on the users. By using a scaling factor, the FOV can be subtly adjusted in real time to reduce the sickness without the notice of the user. This type of implementation requires computation in the change of FOV and has not resulted in any significant difference due to a low experimental population. Third, a dynamic blurring out of the regions that are not in the focused depth of field of the user is another solution [20, 128]. Carnegie et al. claimed that this technique could contribute to the reduction of vergence-accommodation conflicts assessed by SSQ score [20]. However, it was not evident in the paper what method or device was used. Porcino and colleagues proposed two approaches: (1) using two cameras to capture the user's eyes to detect the region of interest, then blur the remaining regions, and (2) extrapolating the focus selection importance of a virtual scene [128]. However, there was no interpretation of the presented data to conclude the efficiency.

In terms of hardware solutions, there are two approaches: motion platforms and direct stimulation injection. Motion platforms stabilise the vestibular system [89], while direct vestibular stimulation uses an electrical signal to mimic a motion signal to the brain [89]. The implementation of the motion platform requires specialised equipment which is not available widely for the user and mainly focuses on military or space simulators. Vestibular system signal injection is promising in reducing or even eliminating VR sickness. However, it is still a debatable topic on how accurate the signal needs to be and how much current is needed [89].

Thirdly, to reduce the negative influence of VR sickness, researchers can ask the subject to take a simple passive break by merely removing the HMD, and adopting a seated posture [169].

As an alternative to passive breaks, *active breaks* can also be an option. There are four different activities for a subject to do after their VR session to wash out the effects of VR sickness. The user can play a peg-in-hole game as a hand-eye coordination practice by trying to put simple objects into specifically shaped holes, perform a rail walking gait movement to gain back the balance in their postural pose, or sit down and let the sickness pass (natural decay/simple break) [21, 89]. According to Champney et al., among these activities, the peg-in-hole game significantly reduced the pointing error rate as a sickness indicator [21], furthermore, all of the three activities contributed to the reduction of postural error significantly for 15 minutes following the VR exposure. After one hour, those practices had no recovery effect.

2.2.2 Visual Fatigue

Visual problems were reported along with VR sickness and ergonomic stress in a 24-hour VR session [169]. In this work, the authors reported visual fatigue along with other sickness symptoms. In other work, visual fatigue (visual discomfort, eye fatigue) [52, 87] was reported as a known VR-related problem and considered a vital issue [47, 118]. Problems with the visual system may reside in the setting of the display itself, such as Vergence-accommodation conflicts (VAC), blue light, and display glare [7, 35, 52, 53, 56, 61, 147, 153, 154, 181]. Hoffman et al. [53], Banks et al. [7], and Hirzle et al. [52] defined VAC as a phenomenon happening with conventional stereoscopic displays where conflicts happened when the accommodation of the eyes is fixed with the display while the object in the virtual environment can be at different distances to the eyes (variation in vergence), and Howarth et al. [56] agreed that VAC is the cause of visual fatigue/eye strain. Besides, VAC may lead to a reduction in ability to fuse disparity images [53] (this fusing ability differs among users [35]) or force the accommodative vergence system to change (self-adaptation) [181]. This adaptive change, in return, even causes more fatigue [147]. Other than VAC, the display may also produce display glare [52, 153] and blue light [61, 154] which are also harmful to the eyes.

There are three technological factors associated with an HMD that cause visual fatigue, including inter-pupillary distance (IPD), flicker, misalignment of optical components, and display properties. IPD is the distance measured in millimetres between the centres of the pupils of the eyes and this adjustment is a built-in feature of conventional HMDs [25, 56, 81, 118, 133]. This parameter differs among the population and is important to creating proper visual effects that change depending on whether a person is looking at near or far objects. If a personal IPD adjustment mechanism is not available in an HMD, the eye gaze will not align with the centre of the optics lens, and blurriness or other issues may occur. Flicker is short for the flicker fusion threshold, and the flicker fusion rate is a concept in the psycho-physics of human vision [25, 52, 81, 89, 126]. The flicker fusion threshold relates to the persistence of vision (refer to the section 2.2.1 for more details). Moreover, the misalignment of optical components involving displays and lenses in a poorly designed HMD can also lead to visual fatigue [113]. Another contributor to the discomfort of the user is the characteristics of the displays [52]. These properties include the increasing of colour values, high chroma values, and high contrast stimuli. Furthermore, the variation of human characteristics also reveals the weakness of VR HMDs regarding adaptations. Factors include their gaze angle [114] variations, and existing visual conditions such as heterophoria [56], where the eyes at rest do not point in the same direction.

Symptoms and Measures

The signs of visual fatigue can be found in a large collection of research works [24, 35, 56, 57, 85, 87, 104, 107, 119, 152, 153, 189, 192], and go along with general sickness symptoms (see Table 2.4). Although visual fatigue is a subset of VR sickness, a closer look at this particular problem reveals distinctive signs that differ from the general health signs of VR sickness, so general VR sickness measures can detect discomfort of the user's body as a whole, but not for a particular system.

Subjective measures for visual fatigue are normally collected using questionnaires, include six in particular. First, the Visual Fatigue Scale (VFS) has 24 items with a 7-level response for each (from absolutely not to completely) [47, 85]. The question-

Table 2.4: The symptoms of visual fatigue have been reported as a mix of both specific visual signs and general health issues [24,35,56,57,85,87,104,107,119,152,153,189].

Visual-related Symptoms	**General-health Symptoms**
Hurt/sore	Tired
Difficult visual focusing	Discomfort
Pulling feeling around eyes	Headache
Dryness	Sleepiness
Blurry vision, coming in and out of focus	Losing concentration
Grittiness	Trouble remembering
Burning	Nausea
Double vision	Pain in head, shoulder, neck
Watery, running eyes	High blood pressure
Red/irritated eyes/flicker	Vomiting
Jumping/swimming/floating words	Dizziness
Pressure feeling in eyes/itchy	Heavy

naire has five factors, including eyestrain, general discomfort, nausea, focusing difficulty, and headache. Second, the Convergence Insufficient Symptom Score (CISS) has 15 items, and at each item there is a 5-level Likert-based answer (never, infrequently, sometimes, fairly often, and always) [87, 141, 142]. The questionnaire has two versions for children and adults to assess near-work activities: video games, hobbies, and pleasure reading. Third, the McMonnies Questionnaire has 12 items, with different answer choices for different question ranges [87, 107]. This subjective measurement assesses dryness and relevant symptoms of the eyes and body (irritation, thyroid abnormality, and arthritis). Fourth, the Visual Function Questionnaire (VFQ) has three parts with a total of 25 items [87, 104]. Fifth, the Computer Vision Syndrome Questionnaire (CVSQ) is a 16-item questionnaire with information about both the frequency and intensity of each item [152]. There are three levels of judging the frequency (never, occasionally, and often or always) and two levels for intensity (moderate and intense). Lastly, the Stereoscopic Three-Dimensional Film Viewing question is a combination of four different sections: spectator's information (demographic data), cinema setting information (floor-plan based sitting position), subjection 3D experience (the length and intensity of the 3D experience), and visual discomfort (vital signs along with dizziness and nausea).

Objective measures contain psycho-physiological measures of cardiovascular, skin, ocular, facial, neural, and behaviour measures. The objective measures for VF share some similarities with VR sickness measures in terms of heart rate or heart-rate variability [46, 83], blood pressure [83], skin condition [46], facial measures [92, 93], EEG signal capture [92], and brain fMRI capture methods [83] (refer to section 2.1.2 for more details). Those methods require on-body sensor deployments that may be unpleasant, and may have some in onset using the equipment. Additionally, there is a relatively recent and specific set of ocular and behaviour measures. For the ocular measures, these include assessing of pupil diameter [52, 90, 180, 189], accommodation/oculomotor response [83, 177, 180, 190], refractive error [52, 82, 189], and visual acuity [189].

The behaviour measures include Event-Related Potential (ERP) [92], blink rate [52,79,83,90,93,144], respiration [46], and fixation and saccade assessments [52]. ERP is a method to investigate electrical activities of the brain based on specific events to determine if the subject is in a stressful situation, and then is extended to measure the biological signals that reflect VF. Besides, Li et al. and Hirzle et al. employed eye tracking, and concluded that the blink rate is proportional to static 3D stimuli, inversely proportional to planer motion stimuli, and that a decrease in blink rate or increase in incomplete blinks is a sign of dry eye or eye strain [52, 93]. Respiration rate is a metric to measure reactions to action, and neural movies [46]. However, there was no solid evidence about the correlation between this particular metric with the reaction of the subject from the paper. In the use of fixation assessment, normal fixation duration is 200 to 600ms in order to perceive visual information. If the subject exhibits a decrease in fixation duration, the number of fixations, and fixation accuracy, the subject may have eye strain [52]. Saccades are short jumps of the eyes between two fixations. If the subject experience any increase in the number of saccades, insignificant saccades or saccade length, the subject may have eye strain or visual fatigue. However, the aforementioned methods require hardware devices that can be specific and professional (other than those used to measure the blink rate). Furthermore, the data needs to be captured at multiple instances of pre-, middle-, and post-experiment for comparison.

Solutions

In combating visual fatigue, the existing solutions include hardware techniques and clinical exercises. Researchers have proposed novel hardware devices such as focus-adjustable lenses, mono-vision, multi-plane, and light-field displays. Focus adjustable lenses allow focal distance matches with the distance to the displayed object in the VE [82]. In mono-vision, the approach is different by varying the focal distance to expand discretization, addressing the range of accommodation with Vergence-Accommodation Conflicts (VACs) [82,83]. One step forward from mono-vision is multi-plane and light-field displays. These technologies share the same implementation of continuously varying the display plane to different focal planes to maintain VAC consistency [82, 83]. However, these technologies need to make progress in minimizing the design for the ergonomics form factor to solve the problems with refresh rate and blur with the multiple focal displays, having fast and precise eye trackers for continuous focal changes, to have mechanical components to move optics along the axis, and to reduce the need for complicated/expensive prisms and lenses [83]. The light field display is a recently proposed advancement in combating VACs and is more compact, but has limitations in spatial resolution and refresh rate [83].

In clinics, doctors use eye exercises to address problems associated with the human visual system in this digital era, when people are facing disturbances in natural eye health from computers, TVs, mobile phones, and other electronic devices [127]. Eye exercises can improve people's vision and eye health [127]. These exercises are also helping with myopia [130], vergence, ocular motility disorders, accommodative dysfunction, amblyopia, learning disabilities, dyslexia, asthenopia, motion sickness, stereopsis, and visual field defects. They can also enhance sports performance [27], tone up extra-ocular muscles, and improve central fixation and visual acuity [3]. Examples of eye exercises and their purpose are presented in Table 2.5. Among the exercises, the Thumb-moving and Figure-eight are simple and address both eye focus and muscle tension which correspond to accommodation and convergence VAC issues by tackling both accommodation and vergence. Although there is no scientific evidence to sup-

Table 2.5: Overview of eye exercise methods and their functions [3, 127, 130]

Exercise	**Focus**	**Muscle**	**Dryness**	**Relaxation**
Thumb-moving/pencil push up	X			
Figure-eight		X		
Left-right/up-down turning		X		
Top-left/bottom-right obliquely looking		X		
Eye circle rolling		X		
Eye close				X
Blinking			X	
Sunning				X
Eyewash				X
Steaming			X	
Cold pads				X

port the use of eye exercises in improving a user's vision [123], practitioners suggest practising eye focus, and underscore the importance of this method to encourage the visual system to do its best [50]. However, despite their promising potential, specific eye exercises in the VR context are not yet available.

2.2.3 Summary

In this section, we studied the health problems of VR sickness and visual fatigue that can be experienced by VR users. We gave an overview of each of the problems, its symptoms and measurement methods, as well as existing solutions. We also discussed the underlying factors of the problems and explanatory theories of VR sickness.

An aggravating factor in the health issues arising from VR use is that conventional HMD design promotes the RW blocking feature to enhance immersion. This leads to difficulty in scenarios and environments that involve not only the VR user and VE, but also physical interaction with nearby objects such as a phone, cup, keyboard, mouse, and even other people. We discuss this issue in the next section.

2.3 Real-world Interactions

Using personal devices or items, and interacting with colleagues are essential tasks in office environments. However, immersive VR poses a significant hurdle for these common tasks because HMDs block out the real-world (RW), known as visual isolation. We now look at these two aspects of office life (interacting with nearby objects and communicating with colleagues) in depth.

2.3.1 Near-object Interaction

Grubert et al. discussed the limitations of current VR HMDs as two-fold: situation awareness and entering text [44]. First, the VR user has very limited situation awareness of the RW, and may get the feeling of physical isolation. Second, control efficiency for making use of the surrounding workplace is also limited, and performance is degraded in things like keyboard typing tasks. Previous research has confirmed that this dilemma negatively affects the user experience by causing discomfort [19,41,106,178]. Interacting with near-field objects is difficult for VR users [19, 178], and also leads to mental frustration when the user has to remove the HMD to find or use them [41, 106]. Aside from discomfort, not being able to see the RW may also lead to minor injuries or accidents in room-scale VR applications [41]. In practice, people need to not only to use keyboards [19,44,106,178] and mice [19,44] to access computer systems for work, but also need to manipulate other items such as phones, mugs, and pen and paper.

Measures

For measuring the efficacy of object interaction techniques, metrics include objective and subjective measures. For *objective measurements*, there are different ways of estimating a user's performance in using objects. Completion time and error rate are the most traditional ways of measuring task performance [10]. The number-of-actions metric counts the needed steps to complete a task [161].

Researchers also use *subjective measures* such as the User Experience Questionnaire (UEQ) [88], NASA-TLX [46, 48] and ITC SOPI [91, 136, 149, 186] to indirectly assess the satisfaction of users in doing interactive tasks. The UEQ questionnaire is an easy and quick assessment to access a user's feelings, impressions, and attitudes towards the use of a system in general. Benchmarking the UEQ score reveals the quality of user experience [148]. The NASA-TLX measures the total workload and is divided into six subjective sub-scales to assess mental demand, physical demand, temporal demand, performance, effort, and frustration. Another approach is to assess the physical space awareness of the user using the ITC-Sense of Presence Inventory (ITC SOPI) questionnaire. These subjective metrics provide a general look into the experience of the user when accomplishing tasks in a user study.

Solutions

Providing VR users with the capability of interacting with the RW can be divided roughly into three tracks: attempts to migrate the physical world into the VE, proposals of mediated access to the actual world, and audio technologies to facilitate access to real information.

One solution is to design the VE as similar as possible to the RW. An example is a one-to-one VR-RW object mapping approach with replicated 3D objects [41]. This approach provides a rich, customizable virtual environment, allowing the user to physically feel its realness. However, this adds extra work, as every interactable object needs to be tracked, and limits the creativity of the VR. Another well-known technique captures the depth of the environment, and provides it to the user [37, 41, 100, 164]. Examples include AR techniques to detect the geometry and semantic information in indoor environments [100], utilization of light detection and ranging (LiDAR) sensors to capture 3D point clouds from the RW [164], and a serious VR game project using the indoor 3D geometry of existing buildings [37]. AR approaches provide a highly detailed and high resolution captured environment. Hartmann et al. proposed the use of multiple depth cameras to provide 3D reconstruction of a space in real time [49].

The solution allows a blend of the reconstructed RW into VR to allow the user to avoid collisions and interact with RW objects. However, they require cameras with high resolution, processing algorithms, significant effort for mapping between VR and the RW, a high frame rate, good depth information, robust alignment and calibration, and time to scan the environment.

Another approach is to provide media to access the RW visually using techniques such as Video-See-Through (VST) [18,19,32,106,138] and Dynamic Immersion (DI) [94]. VST technology involves the use of a camera or multiple cameras to capture the RW scene in centre/front, process it, and feed it into the VE. The representation can be a simple 2D image rendered on a plane, or more-complex object segmentation to extract focused features of the video such as edges, hands, and more [19, 106]. The advantages of this technology are the simplicity and ease of deployment and optimization. However, the quality of the resulting video depends on the resolution of the camera and the image processing techniques, and may also need the depth information. In addition, correctly aligning the 2D view with the 3D view of the user can lead to poor performance, such as reaching for objects in the wrong place, or seeing your own arm in the wrong place.

For enhancing the realness of the captured video feed, a technique called capture ghost character [106] using 3D cameras, e.g. Kinect, to capture the subject's body remotely and feed into the VR as the avatar representing the other talker, can be used. Regarding DI technology, this is the installation of four LCD panels (two for left and right-hand sides and two at the bottom) onto an HMD's periphery to make transparency-controllable windows. Thus, the VR user (or the system) can selectively make the windows opaque or transparent, allowing the user to look out, or be fully immersed. According to Lindeman [94], DI technology has the potential to reduce cybersickness (VR sickness). However, regarding practical applications, the technology reported was only available in a Google Cardboard version. We extend this work to further explore the potential of DI (reported later in this thesis).

To enrich the experience of the user in interacting with the RW, audio and haptic cues can be used. Audio approaches include the possibility of having both the RW and computer-generated (CG) sounds from a VE. There are technologies to offer that information using a bone-conduction headset [95, 96] using "hear-through augmented reality" (HTAR) technology, or "mic-through augmented reality" (MTAR) [95]. HTAR uses the bone-conduction headset to deliver sound waves from the PC through the user's skull, while leaving their ear canals unoccluded for capturing ambient sounds. MTAR technology uses headphones with microphones mounted on them to capture RW sounds and blend them with the CG sounds. Thus the user can select between hearing only CG sound, a mix between the CG and ambient, or only ambient sound. In essence, HTAR is analogous to optical see-through (OST) visual AR, and MTAR is analogous to VST visual AR. Like OST, HTAR has the advantage of providing higher naturalness of signal and requires less computational power, while MTAR, like VST, can offer more flexibility in terms of controlling the blending of CG and RW stimuli for the user. We incorporate these techniques into our work, conduct assessments and report on them later in the thesis. There is also the employment of using audio and haptic as an additional channel in sensing the real world boundary [40]. The solution seems to improve presence, however also seems to induce more workload to the user.

2.3.2 Human Communication

Communication is an essential part of human life [55, 74]. Human communication is adaptive [55], and without this connection people will feel isolated, which has an impact on their health and well-being [55]. An office environment typically involves small groups of people with professional, but also social, relationships, requiring complex communication and synchronization to complete work tasks using social conventions, both formal and informal [33]. In such collaborative environments, colleagues may come to each other's work areas and call each other's names, or contact each other through devices [41], using both visual and acoustic [58] channels. Sonnenwald et al. described this phenomenon as *situation awareness*, environmental information which needs to be gathered, incorporated and utilized [165].

In real life, communication cues (attention, eye-contact, gaze direction, facial expressions, gestures, body and head movements, vocal cues, turn-talking behaviour, use of space, and verbal expressions) are essential for both parties involved in a conversation [62, 65, 115, 140]. Similar findings also apply in the field of human-robot interaction regarding the crucial roles of arm gestures, head movements [97, 110], and especially eye gaze/contact [1, 117, 156]. Conversational behaviours also vary among people, and there are no fixed patterns [140]. Roth et al. also stated that, if there are any delays or longer-than-usual displays of communication cues, for instance, eye contact, miscommunication problems can worsen. In a VR space, early research defined the relationship between a VR user and a non-VR user to be "asymmetric" [43, 45, 84].

Measures

Broadly, the analysis of face-to-face communication or conversation quality of an organisation is the main contributor to productivity, performance, and external customer orientation [193]. The Communication Satisfaction Questionnaire contains a large number of questions regarding eight different interpersonal communication aspects. However, due to its broad content of evaluation toward the health of an organisation, it is not suitable in evaluating a specific part of a conversation, for instance, how engaging the eye-contact, listening, speaking experience is. For evaluation of conversation quality between a real person and a robot, researchers tend to use custom-made questionnaires for assessments [155, 156] rather than using standardised questionnaires, for instance, a User Experience Questionnaire [88]. Unfortunately, this author could not find any standardised methods for assessing communication quality or satisfaction between lay people and VR users, so a customised questionnaire seems to be the optimal choice for shortness, focus, and simplicity.

Solutions

The solutions to support a face-to-face conversation consist of the two main sensory channels of visual and audio. In terms of the *visual channel (for VR users)*, in early research, Hudson et al. [60] proposed a method to provide ambient awareness with a camera and a management model. However, this implementation was confusing, and the camera used was not of sufficient resolution. Another way of capturing ambient awareness is to use sensors (heat, smell, sound, vibration, and light) [5,41]. In the work of Ishii et al., a novel shared drawing medium, ClearBoard, was used to seamlessly integrate an interpersonal space and a shared workspace [63], metaphorically providing a transparent curtain between face-to-face colleagues. With this system, the user could see the opposite colleague while using and drawing on a single mirror board. This implementation needed a draw-able reflective display, projectors, and cameras, but as a result, both people had more eye contact than a typical desktop-based environment.

Among the efforts to bring in a “sense of social connection”, using virtual avatars is a promising area [29, 41, 44, 62, 106, 135, 163, 170, 176]. Avatars are the representation of a user’s body in VR [67, 69, 70, 124, 140, 168]. Avatars can include a head, hands, arms, torso, and legs. This concept is also expandable to the involvement of other people. However, as mentioned above, the communication cues involved in a conversation are complex, nuanced, and dynamic, and they vary among people. Thus, capturing and incorporating these features into VR to make a virtual person is a daunting challenge, requiring new and high-end capture techniques, as well as the computational performance to make the user feel “real”. In some cases, this can benefit from the use of Artificial Intelligence (AI) [140]. Avatars also have individual differences and require syncing with very low delay, or it will take noticeably long to make critical actions [140]. Lastly, to provide the VR user with communication cues, an alternative way is to use VST technology. This technology can provide 2D captures or 3D with depth information, that is robust, simple, cheap and becoming mature due to the wide range of ongoing developments and applications (please refer to the section 2.3.1 for more details). For the *audio channel*, similar solutions can also be found in section

2.3.1.

Concerning *non-VR users*, while Grandi and his team explored the terminology of "asymmetric collaboration" in the AR space [43], Gugeheimer et al. and Kumaravel et al. allowed the non-VR user to be able to see what the VR user saw and have shared exploration and interaction opportunities with the virtual environment using their own HTC Vive controller [45] or a tablet [84]. A different approach for offering a degree of connection between VR and non-VR users is done through a smartphone display mounted on the front of the HMD to display animated eyes [22] or to display a 3D fake covered face-area to make the HMD somewhat "transparent" [102]. Chan et al. used two cameras for eye tracking to link with the digital eyes on the display for providing eye-gaze behaviours. The non-VR user could interact with the VR user by tapping on the display, voice, or hand gestures. However, there was no usability evaluation provided in the paper, and the HMD design was simplified with a 3D-printed housing to mount two back-to-back smartphones and the eye-tracking cameras. The solution from Mai et al. provided a high resolution and realistic detailed modelling of the eyeballs, eyebrows, and eyelids for the 3D face. The approach takes advantage of the front-facing of the smartphone's camera to track the non-VR user and render different viewing angles to mimic natural-looking behaviours. The solution involves the use of different computing algorithms in rendering and smoothing the model. The authors reported the work with no user study and noted its limitations in terms of the field of view of the smartphone camera in tracking, being only possible to track (and look at) one person at a time. In both of the above approaches, there was no report about ergonomics or weight of the proposed solutions. Thus, for supporting an ordinary colleague in face-to-face communication with a VR person, there is a need for a solution that is simple, lightweight, and cheap, but still enabling conversational engagement between the two parties. We present our exploration of such an idea later in the thesis.

2.3.3 Summary

In this section, we explored the problems of needing RW interactions for a VR-HMD-wearing person. The interactions include two key targets, nearby objects and nearby people. For each case, we introduced a general investigation, methods of measures and existing solutions. In the next section, we will provide a summary of the problems so far, and lead into our proposed solutions and their evaluations.

2.4 Chapter Summary

In this chapter, the reader has been equipped with the necessary background into VR technology and two fundamental problems in the use of immersive HMDs, VR sickness and RW interaction. As mentioned, we focus on enabling office workers to maintain a healthy and continuous workflow reducing the need to leave the HMD to accomplish interactions with objects and people in the RW. In the next Chapters (3, 4, 5), we present our contributions to the field, targeting the two main issues for broad acceptance and application of VR for prolonged use, in an attempt to answers the three research questions.

Chapter 3

Active Breaks Health Recovery Technique

Prolonged use of virtual reality (VR) head-mounted display (HMD) systems without removing the HMD remains a challenge due to many factors. One is that the eyes suffer from visual fatigue arising from Vergence-accommodation conflicts (VACs) caused by stereoscopic HMDs, with effects that progressively increase over time and result in symptoms of VR sickness. Existing solutions mainly focus on the proposal of novel and sophisticated hardware displays to overcome conventional HMD drawbacks, as well as using simple passive breaks to interrupt the VACs (natural decay). Outside of the VR context, clinics for people with eye-fatigue symptoms or who have difficulty seeing in daily life are given specific exercises such as "Thumb-moving" for focal distance adjustments or making a "Figure-eight" by rolling the eyeballs for exercising the eye muscles. These two practices efficiently help the eyes rapidly recover back to a normal state. In this work, we mainly focus on the introduction of a recovery technique called "Active Breaks", which is the implementation and adaptation of the Thumb-moving and Figure-eight exercises into the VR space, and investigate its impact. The user study was approved by the University's Human Ethics Committee (Application number: 2019/26/LR-PS; see Appendices A and D for relevant documents).

3.1 Introduction

VR technology is now capable of delivering an immersive experience to users to stay in computer-generated worlds for extended periods. However, providing a prolonged VR session without leaving the HMD remains a challenge due to the problems including VAC, blue light, and display glare [7, 35, 53, 56, 61, 147, 153, 154, 181]. One significant issue is the VAC coming from conventional stereoscopic displays where conflicts occur when the eyes' accommodation is fixed on the display while the object in the virtual environment is at a different distance to the eyes (variation in vergence) [7, 53]. This can result in tiredness, stress, and general discomfort for the visual system [7, 9, 24, 25, 35, 47, 53, 56, 57, 77, 81–83, 85, 87, 89, 113, 114, 118–120, 126, 133, 147, 153, 169, 181, 185]. Although work has been done on the proposal of new VR displays such as focus-adjustable lenses, mono-vision, multi-plane, and light-field displays [82, 83], there is still a need for a simple and more cost-effective solution. As mentioned, Thumb-moving and making a Figure-eight are widely used in clinical settings. In the Thumb-moving exercise, the person uses their dominant hand to form a thumbs-up pose (see Fig. 3.1, left), focuses on the thumb tip, and moves the hand away and towards them, typically about ten times. For the Figure-eight exercise, the subject looks at a board with a large horizontal "8" on it, focuses on the centre dot, and then rolls their eye-balls following the directed arrow on the black path while keeping their head steady (Fig. 3.1, right). These exercises offer focal adjustment and ocular muscle practice to strengthen the muscles and help the eyes rapidly recover back to a normal state [3, 27, 127, 130]. Despite their practical efficiency, these exercises have not yet made their way into the VR space with any proper evaluation.

The main idea of this work is to get the VR user to practice the same exercises (with modifications for VR use) as in the clinics. We investigated the effects of those exercises (Thumb-moving and Figure-eight, together called "Active Breaks") for VR-user health in a study with three conditions. In one condition, we provided virtual versions of Active Breaks in VR (VRE) to allow the users to perform those exercises while still wearing the HMD. In another, the users performed the exercises in the RW

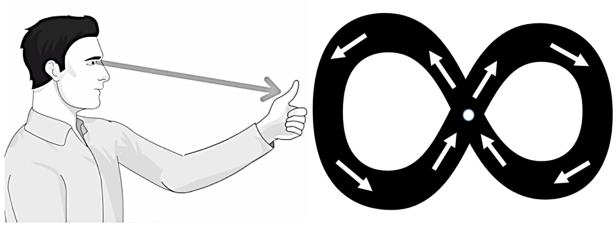

Figure 3.1: The Thumb-moving exercise allows the exercising of the eyes with different and continuous focal distances (left), while the Figure-eight exercise re-trains the eyeball muscles (right).

(RWE) by taking off the HMD at some points during the VR experience. Lastly, we collected the Baseline data, where there were no exercises involved, thus providing the "normal" case experienced by most VR users today. We investigated the effects of the exercises and conditions on the health (both visual and general health) of the users, considering the following three research questions: 1) "Will the VR and RW exercises reduce eyestrain/visual fatigue for the VR user compared to the Baseline?", 2) "What will be the level of presence of the virtual exercises in comparison with the RW exercises and Baseline?", and 3) "Will multiple exercise sessions have a positive effect?"

3.2 Method

In this section, we describe our experiment to investigate the impact of applying the two eye-relaxation exercises for reducing visual stress and VR sicknesses. We investigated three hypotheses:

- **H3.1**: The RWE condition will reduce visual fatigue more than the VRE condition, while the Baseline condition will show an increase in eye discomfort.
- **H3.2**: The VRE condition will result in a higher sense of presence in VR compared to the RWE condition, but lower than the Baseline condition.
- **H3.3**: After doing a second set of exercises, the positive impacts will remain with the user longer than following the first session.

To explore our hypotheses, we used a mixed factorial design with one independent variable (exercise type) across three levels (VRE, RWE, and no-exercise). We used four dependent variables for measuring the sense of presence [149]: the eye-blink rate as an objective measure [79, 83, 90, 145], and Computer Vision Syndrome Questionnaire (CVSQ) [152], Simulator Sickness Questionnaire (SSQ) [143], and Igroup Presence Questionnaire (IPQ) as subjective measures. Previous research reported a positive correlation between blink rate and level of sickness [79]. In a normal condition, the eyes have a specific blink rate for individuals, from 6-30 times/min. Kim et al. suggested that the eye blink rate might decrease during the viewing of high-intensity and realistic content, and the rate shows a decline from the natural environment to desktop display to VR HMD [79]. Practically, the blink rate can be captured with a pair of small infrared cameras, which influence the smooth experience of the user less than body-mounted sensors. Furthermore, we used the CVSQ for visual fatigue assessment in both frequency and magnitude of severity, and the questionnaire partially overlaps with the SSQ (in assessing general health). Overall, using both the CVSQ and SSQ will cover both eye fatigue symptoms and the related general health problem of VR sickness. In addition, we employed the IPQ questionnaire for measuring differences in the sense of presence in the experimental conditions. We also screened the participants at the beginning of the user study session using the Convergence Insufficiency Symptom Survey (CISS) to identify outliers with abnormal vision [87, 141, 142].

For a more in-depth evaluation, we also asked subjects for their preferences of the conditions at the end of the experiment, by rating each of them on a five-point Likert scale from “Not at all helpful” to “Very helpful.” We then used the data to determine the preferences of the users for the individual exercises (either Thumb-moving or Figure-eight), and conditions (VR-based or RW-based version).

3.2.1 Study Design

In the experiment, we considered the use of the Active Breaks technique during VR break sessions using both VR-based and RW-based versions. The main task was to

Figure 3.2: The VRE (a & b) conditions with a virtual hand and a virtual board, and RWE (c & d) conditions with participant's hand and a physical board.

watch videos within the HMD. We then used a between-subjects design for the user study, with two conditions, VRE and RWE, and 10 participants per condition.

We counterbalanced the order of experimental conditions and differentiated video materials for the non-practice condition and eye-practice conditions while keeping the order of the presented videos fixed for those conditions. Moreover, we fixed the order of the eye exercises starting with Thumb-moving and then Figure-eight. Overall, each user took about 1 hour and 15 minutes to complete the study.

3.2.2 Conditions

The experiment had three conditions:

VRE: The VR Exercises condition required the subject to spend 15 minutes watching a movie, then perform virtual exercises, another 10 minutes of movie watching, then virtual exercises, then five minutes of movie watching, and finally answering questionnaires. We used videos of different lengths for investigating the correlation between the duration of videos and the blink rate. In this condition, we had a virtual hand in a thumbs-up pose showing in the middle of the scene (Fig. 3.2a) for the virtual Thumb-moving exercise. The virtual hand automatically moved away and towards the participant for them to focus on, and stayed visible for 40 seconds (corresponding to 10 cycles). For the Figure-eight exercise, a virtual board for eye path tracing was presented for the same amount of time (Fig. 3.2b). There were also text instructions to assist the participant with steps and actions throughout the session. At the end of this condition, the participant answered three questionnaires CVSQ, SSQ, and IPQ on a laptop. Af-

Figure 3.3: The Vive Pro HMD with add-on Pupil Labs eye tracker.

ter the last condition of the experiment, the subject also answered our user-preference questionnaire.

RWE: In the RW condition, the procedure was similar to the VRE condition. However, the subject performed the exercises in the RW after taking off the HMD following the viewing of each movie in the HMD. For the Thumb-moving exercise, the subject used their dominant hand to perform it (Fig. 3.2c). In the Figure-eight exercise, we installed a paper-based board representing the eye trace path in front of the chair with similar texture and dimensions to the one in VRE (Fig. 3.2d). The participant practised a similar ten iterations for each exercise. The subject also filled in their preference at the end.

Baseline: In the Baseline condition, we did not provide any exercise sessions or breaks. The only task was to watch each movie one after another in the HMD continuously until the end, or when the subject decided to stop. Afterwards, the participants answered the same questionnaires and stated their preference.

3.2.3 Materials

We used an HTC Vive Pro HMD to render the VE using the Unity 3D game engine on a PC (Intel Core i7-8700 @3.2GHz CPU, 32GB RAM, Windows 10 Enterprise 64bit, and NVIDIA GeForce RTX 2080 GPU), and we controlled the data logging and system control on the same PC. For eye capturing purposes, we installed a pair of Pupil Labs[1] infrared cameras (Fig. 3.3). These Pupil Labs cameras captured eye movements and blinks during the study, and we counted the blink rate manually using the captured videos. The video material for the participant to watch was from an open-access channel for computer-generated 3D animated videos[2]. We downloaded the videos at 720p resolution and then randomly picked the movies with different genres. There were six movies including: "Big Boom" (Sci-Fi), "Ocean Maker" (Action), and "Ruin" (Action) for the Baseline condition, and "Green Light" (Sci-Fi), "Le Gouffre" (Adventure), and "Alarm" (Neutral) for both the VRE and RWE conditions.

VRE setup: We built a simple environment to represent a RW office space (Fig. 3.4, left). The created scene (using Unity version 2018.3.14) included a virtual chair, a desk and a simple curved display for movies. The bending degree was 107 degrees. The virtual space was designed to be consistent with the corresponding distance and size in reality. We lit the scene with an ambient light source to give office lighting conditions. We also used the screen to display text-based instructions for the participant. In this VE, there was also the virtual hand placed between 10cm (nearest thumb-tip to the eyes) and 28cm (farthest thumb-tip to the eyes), and the virtual board positioned at 28cm from the person for the VRE condition, to render the virtual items with a similar appearance to the RW condition. Since the virtual hand can have perceptual or cognitive impacts on participants [4, 66, 68, 69, 71, 191], we designed a generic right hand with a medium skin colour texture.

RWE setup: The facilities of the experiment were similar to the virtual VRE office with a table and chair with armrests. We set the height of the chair to ensure the eye ray of the participant was perpendicular to the centre dot of the physical Figure-eight board (the head-to-board distance was 70cm). The height was also equal to the virtual Figure-eight board in VR (Fig. 3.4, right). The location of the leg of the chair was marked on the floor for pinpointing the participant's position regarding the experimental facility. We allowed the participant to interact with the VR using a Vive controller with

[1]https://pupil-labs.com/products/vr-ar/
[2]https://www.youtube.com/channel/UC-1rx8j9Ggp8mp4uD0ZdEIA

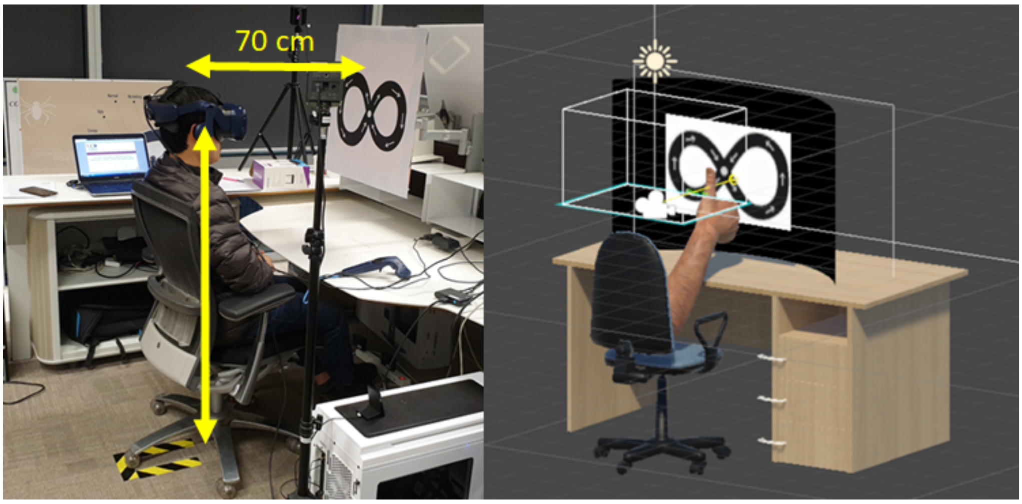

Figure 3.4: The physical space (left) and virtual space (right) of the experiment.

a trigger button and touch pad. The trigger button was to start each movie and to obtain further instructions when the movie ended, and the touch pad was used to start doing the VR-based exercises. We rendered the controller in the VE to help the participant easily locate it while wearing the HMD.

3.2.4 Procedure

Participants started with an introduction session that explained the purpose of the user study, described the tasks, instructed how to do the exercises, and gave them an opportunity to ask questions.They then filled in and signed a consent form, and answered demographic and screening questionnaires on their health conditions on a laptop. Using a counterbalanced order, subjects watched two blocks of three movies, with one condition assigned to each block in one of the following four orders: Baseline then VRE, Baseline then RWE, VRE then Baseline, or RWE then Baseline. The experimenter then helped each subject to put on and adjust the HMD, made sure they could find the controller and identify different relevant controls (trigger, touch pad), adjusted the chair to the correct height and position in front of the desk, and reminded them of the flow of the current condition before starting the capturing software for later data analysis (blink rate counting). After finishing the first condition, the subject took off the HMD and answered the questionnaires on the laptop, then continued with the second condition after

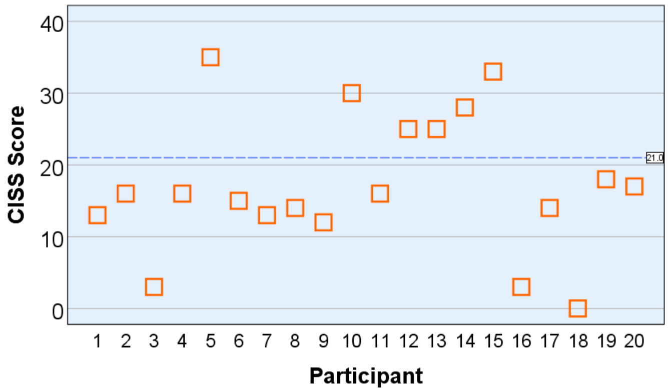

Figure 3.5: The screening CISS questionnaire reported participants no. 5, 10, 12-15, may have visual distress before entering the experiment.

a five-minute break. At the end of the second condition the subject answered the same questionnaires with an additional survey of preference. The final step was thanking the subject for their time and giving them a $15 voucher.

3.2.5 Participants

To choose a suitable sample size, we used the G*Power v3.1.9.4 software with "F-tests" for test family, "ANOVA: Repeated measures, between factors" for a statistical test, and input parameters to achieve a large effect size of 0.8 and power of 0.95 with three groups and four measures. The implemented parameters resulted in a proposed sample size of 20.

We then recruited 20 participants (age $M = 28.8, SD = 5.46$, eight females). Among the 20 participants, seven had never had experience with VR, four of the rest used VR very often at "a few times per week" frequency, and one reported a previous severe VR sickness experience through the demographic questionnaire. For eye condition, all of the participants claimed a normal eye state; 12 corrected to normal by wearing either glasses or contact lenses. As the screening step before entering the first condition, the CISS screening survey took place to capture data of possible participants with pre-existing visual stress.

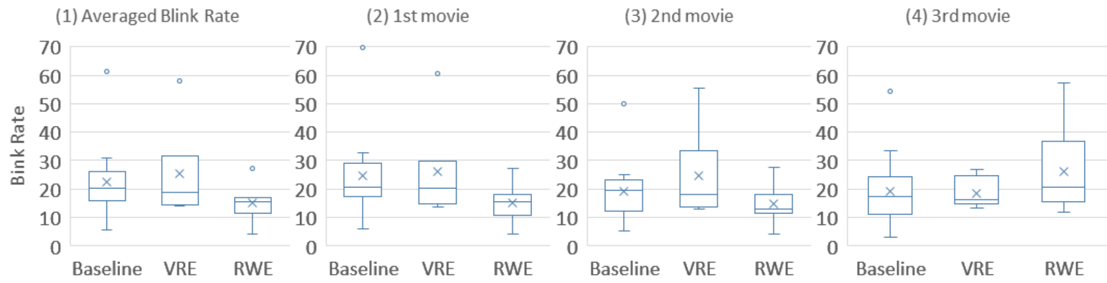

Figure 3.6: The mean overall Blink rate by condition (1), Blink rate during the first (2), second (3), and third movie (4).

3.3 Results

3.3.1 Eye Condition Screening

A pre-experiment analysis revealed six responses with a higher score than the normal margin of 21, which means these subjects may have been experiencing visual stress before entering the experiment (Fig. 3.5). Thus, we excluded those data from further analysis, leaving us with data from 14 subjects.

3.3.2 Blink Rate

We manually counted the blinking rate per minute from the captured videos (see Fig. 3.6-1). A Kruskal-Wallis test for the averaged Blink rate per condition showed no significant differences of means ($\chi^2 = 2.996$, $p = 0.224$).

We analysed the Blink rate further by breaking down the entire condition length into three separate movies (the first 15-minute, the second 10-minute, and the third five-minute movie) to investigate the potential positive impact of the implemented exercises on the Blink rate during those movies (see Figs. 3.6-2 to 4). Note that the participant only performed exercises after watching the first and second movies. Kruskal-Wallis tests for the Blink rate during the first, second, and third movies per condition showed no significant differences of means ($\chi^2 = 4.512$, $p = 0.102$), ($\chi^2 = 1.872$, $p = 0.392$), and ($\chi^2 = 0.880$, $p = 0.644$) correspondingly.

Looking closer, we analysed the influence of the times of doing Active Breaks (after the first time and second time of performing exercises by evaluating the Blink rate during the second movie and third watching) compared to the beginning period prior to any Active Breaks involved for the particular conditions of VRE and RWE (see Fig. 3.7). A Kruskal-Wallis test for the Blink rate over the different stages for the VRE and RWE conditions showed no significant differences of means ($\chi^2 = 2.561$, $p = 0.464$), ($\chi^2 = 2.876$, $p = 0.237$) correspondingly.

3.3.3 CVSQ

The data visualization for CVSQ is in Fig. 3.8. A Kruskal-Wallis test showed no significant differences of means ($\chi^2 = 2.601$, $p = 0.272$). As a result, we cannot find support for H3.1.

3.3.4 SSQ

The SSQ evaluated the VR sickness level after finishing each condition. A Kruskal-Wallis test for the total score per condition showed no significant differences of means ($\chi^2 = 1.513$, $p = 0.469$) (see Fig. 3.9-1). As a result, we cannot find support for H3.1. However, even though it was not significant, we think there is at least a trend that *any* eye exercises may help in terms of VR sickness, but this is just a conjecture

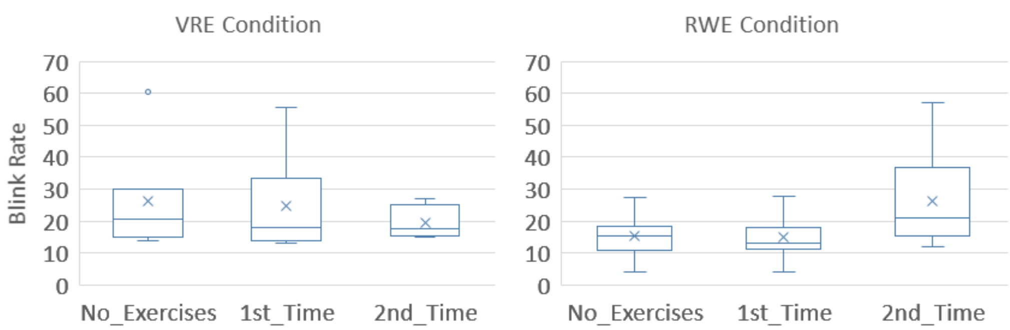

Figure 3.7: The Blink rate after the first time (left) and second time (right) performing Active Breaks

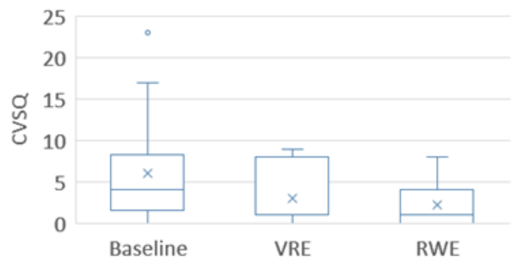

Figure 3.8: The CVSQ results.

based on the results. In an attempt to break down the data to evaluate sub-components, we calculated scores for Nausea, Oculomotor stress, and Disorientation and applied the same Kruskal-Wallis test. However, there were no significant differences for Nausea ($\chi^2 = 2.054$, $p = 0.358$), Oculomotor ($\chi^2 = 2.324$, $p = 0.313$), or Disorientation ($\chi^2 = 2.505$, $p = 0.286$) (see Fig. 3.9-2 to 4).

3.3.5 IPQ

The IPQ evaluated the level of VR presence for subjects through different experimental conditions. As described in H3.2, we expected to see a similar transition of this indicator across different conditions with the same pattern. We performed Kruskal-Wallis tests on the scores for General Presence (GP), Spatial Presence (SP), Involvement (INV), and Realism (REAL) over conditions (Fig. 3.10). We found no significant differences ($\chi^2 = 2.042$, $p = 0.360$), ($\chi^2 = 2.393$, $p = 0.302$), ($\chi^2 = 0.173$, $p = 0.917$), and ($\chi^2 = 0.421$, $p = 0.810$) correspondingly. Thus, we found no support for our H3.2. We present a descriptive report for all of the analysed data in Table 3.1.

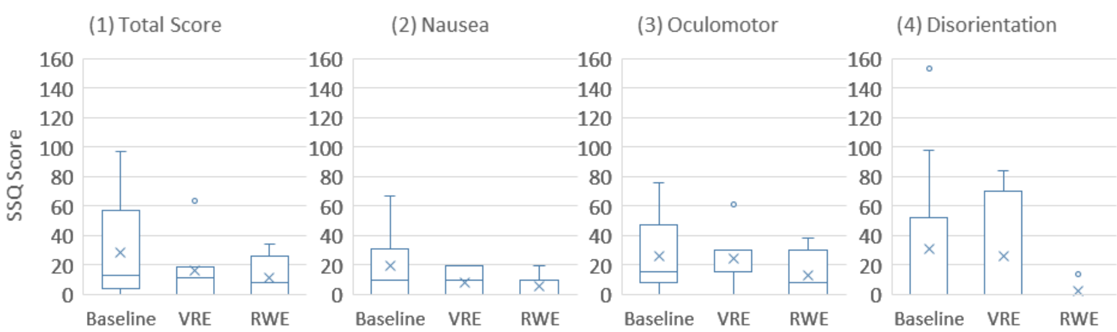

Figure 3.9: The SSQ results.

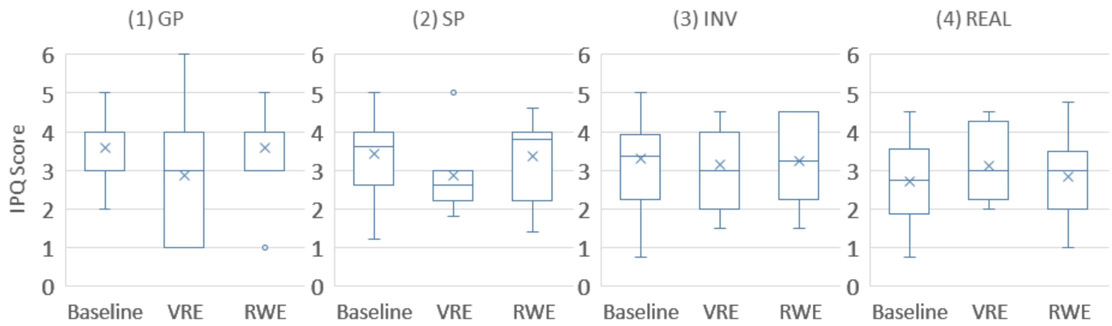

Figure 3.10: The IPQ results.

Table 3.1: Descriptive analysis for Blink Rate (average, during watching the first, second and third movie), CVSQ, SSQ and IPQ, with subscales, Mean (Standard Deviation).

	Baseline	VRE	RWE
Blink rate (entire condition)	22.58 (12.86)	11.04 (15.58)	4.44 (6.94)
Blink rate (during the 1st movie)	24.73 (14.79)	10.92 (16.11)	4.67 (7.06)
Blink rate (during the 2nd movie)	19.23 (10.63)	11.32 (15.38)	5.01 (7.25)
Blink rate (during the 3rd movie)	19.27 (13.04)	4.11 (5.19)	11.98 (16.03)
CVSQ	6.00 (6.74)	3.14 (3.79)	2.20 (2.97)
SSQ_Total	28.58 (31.86)	14.35 (22.20)	10.69 (13.31)
SSQ_Nausea	19.08 (23.37)	7.01 (8.58)	6.23 (7.51)
SSQ_Oculomotor	25.99 (24.82)	14.23 (19.29)	12.04 (14.98)
SSQ_Disorientation	30.82 (47.97)	29.54 (36.32)	3.41 (5.26)
IPQ_GP	3.57 (0.94)	1.31 (1.77)	0.90 (1.27)
IPQ_SP	3.41 (0.94)	0.69 (1.04)	0.90 (1.14)
IPQ_INV	3.29 (1.16)	0.88 (1.11)	0.79 (1.10)
IPQ_REAL	2.71 (1.06)	0.77 (0.97)	0.92 (1.21)

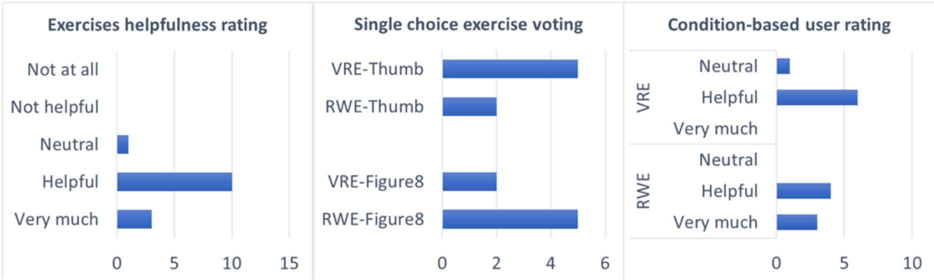

Figure 3.11: Participant preference on the level of helpfulness of the two exercises (left), the most preferred exercise (middle), and a classification of voting for conditions (right).

3.3.6 Helpfulness and Subject Preference

Each participant provided their preference at the end of the two conditions (Fig. 3.11, left). From the graph, most participants reported the implementation of the two exercises, either in VRE or RWE, as “Helpful” or “Very helpful” for RWE. To obtain a deeper understanding of the reasoning behind their choices, we forced participants to choose one exercise that they preferred (Fig. 3.11, middle). It seems subjects tended to favour “Figure-eight” for the RWE condition, and “Thumb-moving” for VRE.

In addition, we found that participants were more satisfied with doing the exercises in the RW condition with three extreme Likert ratings of “Very helpful” and four for “Helpful” for RWE and the VRE condition scored mostly “Helpful”, with only one subject giving it a “Neutral” rating (Fig. 3.11, right).

3.4 Discussion

In this user study, we introduced two eye-relaxation exercises from clinical contexts into the VR space. These two exercises were adapted using two scenarios, doing them in the RW (RWE) and in VR (VRE). The aims were to evaluate the subjective responses of the participants with the introduction of eye exercises, measure the influence of the exercises on subjects and attempt to find support for making the VRE the preferred choice, in order to allow users to stay inside the HMD.

Regarding the system preference, we found that most of the subjects were satisfied with the introduction of the exercises compared to the condition with no exercises. We observed a trend where the participants rated the efficiency of doing exercises in the RW as higher than in the VR. There was also a higher preference for Thumb-moving for VRE and Figure-eight for RWE.

For the rest of the subjective measures and objective blink rate, we did not find significant differences among the conditions to support our hypotheses fully. For H3.1, both of the objective blink rate and objective questionnaire analyses showed no significant differences when comparing the effectiveness of VRE with the remaining conditions. H3.2 was also not supported with no significant differences found in the IPQ questionnaire. In comparing the effect of performing Active Breaks over time in a VR session (H3.3), we observed an increasing tendency of blink rates after users completed the second round of eye exercises in RWE condition. However, in VRE, it seems that the blink rate had the opposite tendency. The statistical analysis resulted in no significant difference among conditions.

3.5 Limitations and Future Work

We can identify several improvements needed concerning the user study. In terms of the user experience, the virtual thumb speed needs to be adaptable to the user's desired pace and could be done with a calibration from the user. Besides, for the VRE, it may be more realistic, as suggested by one participant, if we had used the VR controller to drive the virtual hand's movements. Regarding the user study design, a uniform genre of the used movie may help to reduce the potential influence of the video content to the blink rate of the user. Additionally, we should provide a form of break for the Baseline condition, such as a blackout, with the amount of time equal to the amount of time where the subject had to do exercises in the other conditions, to provide more consistency across all the conditions. Lastly, an experiment to focus primarily on evaluating the efficiency of the RW exercises with additional objective measures and with a typical workday experience with VR would be a more practical assessment for the efficiency of the exercises.

Regarding the implementation of Active Breaks, only the Figure-eight exercise seems appropriate in VR, as the other exercise might not be effective, due to the fixed focal distance of the user's eyes relative to the HMD's displays. The RW versions show potential with their naturalness and efficiency, but there was no scientific foundation to support use in VR. Besides, Active Break is only targeting VAC issues (ignoring other factors, such as display or lens-related issues), and seems to be undervalued due to the typically short VR exposures, experimental designs, recruited populations, and lack of professional measuring devices.

3.6 Chapter Summary

In this work, we migrated and adapted eye exercises from traditional eye-health clinics to form the Active Breaks technique for visual health recovery (regarding research question 1). This method required the user to do recovery exercises during their VR breaks. The exercises included the Thumb-moving for training eyes at a gradually different focal distances, and Figure-eight for training the eye's muscles. We designed these exercises in RW and VR versions. The RW Active Breaks (RWE condition) required the user to do the visual recovery exercises in the RW, and the virtualized version (VRE condition) let the users do those exercises within VR without having to leave the HMD. We designed a usability test to investigate the efficiency of the techniques in terms of visual recovery, user preference, sense of presence, the potential of induced VR sickness, and objective data of blink rate. Our results showed that although there was no evidence to support all the hypotheses fully, the Active Breaks technique received a high rate of preference from the users (sample size of 14 subjects after excluding 6 participants due to the potential prior visual stress). Lastly, we summarized the limitations and future works for further research and development.

Support for long-duration VR experiences within a standard workflow office environment that enables people to interact with their physical world while wearing an HMD is the next research question to be discussed in the next chapter.

Chapter 4

Multi-Channel Dynamic Immersion HMD

In the previous chapter, we tackled one aspect of VR for prolonged use, visual fatigue as part of VR sickness, using an Active Breaks health recovery technique. In practice, however, the VR user also experiences another issue, which is difficulties in interacting with their surrounding RW objects while wearing a conventional VR HMD. Although the user can take off the HMD to carry out such interactions, this causes discomfort, disorientation, breaks in presence and even frustration. Thus, for promoting a long and comfortable VR experience, there is a need for supporting the user with RW interactions without having to leave their HMD, and to facilitate smooth transitions between VR and RW experiences. To address this, we present a study of the usability a new HMD which allows the VR user to easily switch between tasks in VR and the RW using multiple visual channels dynamically to obtain a wide field of view from the RW environment. We call our approach Multi-channel Dynamic Immersion (MDI). The user study was approved by the University's Human Ethics Committee (Application number: 2018/37/LR-PS; see Appendices B and D for relevant documents).

4.1 Introduction

According to a recent report by Gartner [137], immersive technologies will substantially change how we work and interact with each other. The report predicts that by 2022, early adopters will replace 20% of their 2D screen-based work with interactions using immersive interfaces. Future HMDs will combine a variety of possibilities to display and merge real and virtual content. Hence, it is of utmost importance to explore ways of allowing people to effectively and efficiently combine immersive technology work with day-to-day activities in the RW. In this chapter, we propose an HMD that allows seamless and dynamic switching between work in immersive VR and the RW, as well as graceful ways of mixing the two.

The availability of high-resolution, real-time stereo rendering HMDs has made delivering immersive VR experiences not only achievable but commonplace. While wearing an HMD, the computer-generated VE covers almost all of the user's visual field, and the black foam rubber around the eyes (designed for the user's face protection) blocks any visual distractions from the RW. We call this phenomenon Visual Isolation (VI), whereby the user can focus on the VR content to improve the immersion level of the VR experience. However, VI also brings with it some new problems, because users have difficulty interacting with the physical world around them unless they take off the HMD. For example, it is not easy to pick up a nearby mug to take a sip of water or grab a doughnut while wearing an HMD, since the VR has no idea of the location of these nearby objects. Similarly, VR developers often need to switch between their development environments and VR during the code-test-code-test... cycle. The discontinuity produced by continually putting on and taking off of the HMD can lead to degraded experiences, increased physical fatigue and other negative feelings like VR sickness. To address the limitations of current HMDs, we propose a new HMD which enables the user to see the RW without taking it off, by adding optical and video channels, thereby encouraging more natural interaction when handling RW contexts and objects.

In terms of existing solutions, Lindeman et al. showed an HMD prototype, Dynamic Immersion (DI), that attached controllable LCDs around an HMD to allow the user to see the peripheral view if needed [94]. The prototype, based on Google Cardboard, consisted of four LCD panels (two on the sides, two on the bottom) with simple manual control. McGill et al. used a web-camera in front of the HMD to provide a frontal view (video-see through, or VST) to the VR user [106]. Each of these approaches provides a partial solution to the RW viewing problem. We combine these visual channels, and provide transparency-controllable LCD panels and a more expansive angle view of the RW using a fish-eye lens for a camera (see Fig. 4.1). With this new MDI device, we aim to provide users with a better experience when seeing and interacting with the near-field RW from inside a VR HMD. We investigated the usability of our MDI HMD compared to existing approaches, including a DI HMD, VST HMD, and a generic HMD (Baseline) for different VR-related tasks. In this experiment, we intentionally designed a simulated daily office environment, and also provided everyday office-related tasks (e.g., keyboard typing, responding to a phone call or text, moving a cup). Although the results showed no significant differences using measures of task performance, workload, presence, or VR sickness, users tended to select our MDI HMD as their preferred device for usage. Observations during the experiment and comments from participants were encouraging and suggested substantial future improvements.

4.2 Method

In this section, we describe the design of the four types of HMDs included in our experimental design to investigate the effects of MDI compared to the other three HMDs using both qualitative and quantitative measures. In the study, participants had to complete the primary task of typing a set of sentences in VR and three secondary RW tasks, moving a cup, responding to a phone call, and responding to a text message. We expected that providing multiple optical channels (frontal and peripheral views) would keep a high sense of presence, resulting in better interactions with the RW and improved usability over the others, and formulated the following hypotheses:

- **H4.1**: Using an MDI HMD will result in high usability (shorter completion times for RW tasks, lower mental workload, high sense of ease of control, and be more preferred) compared to other HMDs.

- **H4.2**: Using an MDI HMD will result in a higher sense of presence compared to other HMDs.
- **H4.3**: Using an MDI HMD will result in lower VR sickness compared to other HMDs.

4.2.1 Materials

We chose a low-cost, mobile-based VR platform (Merge HMD[1]) with an interpupillary distance adjustment mechanism built in. We used a soft foam body as the basis for our work as this was easier to install the LCDs, controller, and fish-eye camera lens into than HMDs made of plastic. We implemented four types of HMDs based on this platform, using the same smartphone (Samsung S9[2]) to render the VR scene, capture the RW channels, and connect to a Bluetooth keyboard for the typing task in VR. Since we attached additional devices to the HMD, we measured the weight before we ran the study. The generic HMD weighed $539.17g$, the VST HMD $574.43g$, the DI HMD $626.22g$, and the MDI HMD $661.48g$. The average was slightly heavier ($M = 600.33g$, $SD = 54.22g$) than commercial HMDs ($470g$). We developed the system using Unity3D, Android Studio, and Visual Studio Community Edition.

- MDI: We created the MDI HMD by combining DI and VST technology, providing a wider RW FOV to the user at the press of a button (see Fig. 4.1a). We installed four LCD panels around the HMD (two on the bottom, one on each side), driven by an Arduino board, and powered by, and communicating with, the phone. The subject could toggle the transparency of the LCD panels in unison with front-camera rendering (ON and OFF) by pressing either the left or right button on top of the HMD. Though the Arduino supported this, we did not provide

[1] https://mergeedu.com/headset
[2] https://www.samsung.com/nz/smartphones/galaxy-s9/

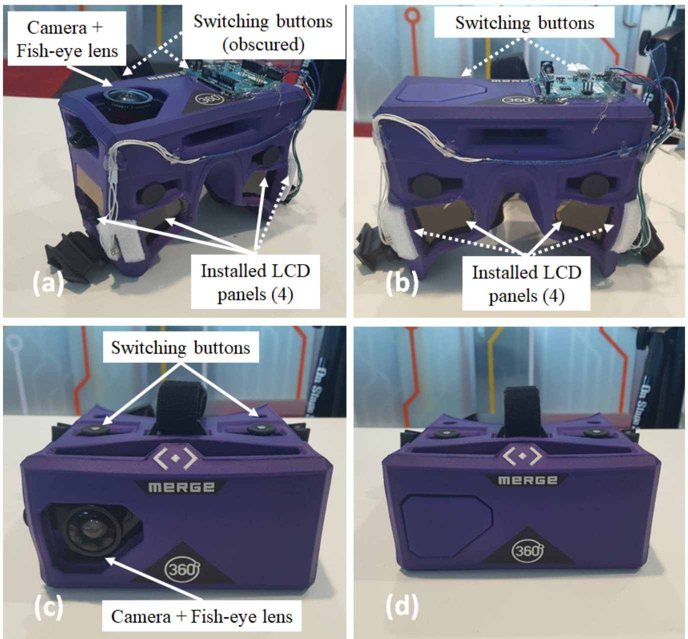

Figure 4.1: The MDI HMD (a), the DI HMD (b), the VST HMD (c), and the generic HMD (d). Dashed arrows imply obscured parts.

multiple levels of opacity for the LCD panels. In opaque mode, most of the light from outside was blocked, while in transparent mode, there was no difficulty seeing the outside world (see Fig. 4.2). The VST feed from the back-facing camera on the phone was displayed on a virtual camera plane in the VR when the subject used a button and a reticle to activate a virtual plane. Due to the camera location and narrow FOV, we mounted a fish-eye lens[3] using a 3D printed bracket on top of the original lens. This increased the FOV of the camera from 60 degrees to 140 degrees.

- DI: The DI HMD used the same setup as the MDI, but we turned off the VST feature. Pressing either of the toggle buttons on the HMD toggled the LCDs between transparent and opaque modes (see Fig. 4.1b).

- VST: The VST HMD used only the fish-eye lens. Pressing either of the toggle buttons on the HMD toggled the video stream ON and OFF (see Fig.4.1c).

- Generic HMD: A generic HMD was user as a baseline (see Fig. 4.1d), to allow us

[3]https://www.pbtech.co.nz/product/MPPCYG0242/Cygnett-CY1736UNLNS-1-packClip-on-Wide-angle-lens

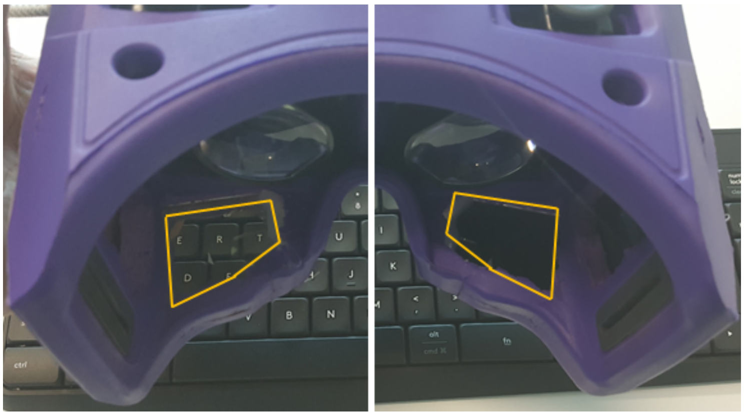

Figure 4.2: Side-by-side example of the LCD panels (outlined in orange) in transparent (Left) and opaque (Right) mode.

to compare with the other three HMDs. The toggle buttons were disabled. When a subject wanted to carry out RW tasks, the HMD had to be removed (or moved aside) momentarily.

We developed an application using Unity for ease of virtual space construction using the Google VR SDK [4] and a self-developed plugin for serial connection between the Arduino controller with Unity using Java_Native_Object.

4.2.2 Design

In this experiment, we used a within-subjects design with one independent variable, type of HMD, with four levels as described above. To investigate the effects of MDI, we assumed the scenario of a VR researcher or developer working in an office environment. We designed a similar office environment in both of the real and virtual environments to minimize degrading the immersion due to the mismatched plausibility and place illusion [160] when the subjects switched between virtual and real space [71]. Subjects had to conduct a simple typing task in the VR and respond periodically to events or requests coming from the RW. All tasks, both in VR and the RW, were done in a seated position. To avoid learning effects and both mental and physical fatigue, we varied the order of the HMDs and tasks using a Latin square.

[4] https://developers.google.com/vr/develop/unity/get-started-android

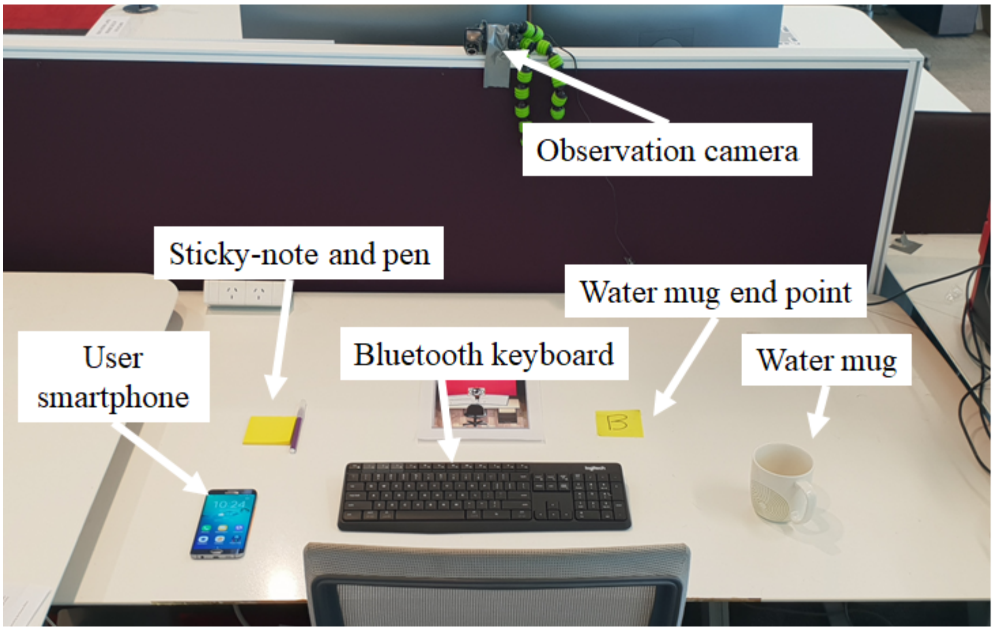

Figure 4.3: The physical environment of the experiment.

Environments

Physical Office: We designed a typical office environment in the experiment room. We placed multiple objects (e.g., sticky-notepad, pen, smartphone, and water mug) around a Bluetooth keyboard (Fig. 4.3). We installed a web-camera at the top of the partition to record participant behaviour, capturing only the torso and hands. The physical environment setup was identical for every participant in every trial.

Virtual Office: The virtual office environment was similar to the physical office environment (see Fig. 4.4). We placed light sources in the VR space to match the ambient light levels of the RW to avoid any unexpected visual distraction. In the VR office, subjects typed the given sentences shown on the left-hand VR monitor using a physical keyboard. The right-hand VR monitor showed the typed text of the subjects so they could check their progress and correct errors. The white plane shown on top of the screen could be selected by the subject using a head-controlled reticle to point and the buttons to select, which would activate the VST display and DI panels. Once activated, the camera stream would be shown on a double-sided rectangle (Fig. 4.5) and the LCD panels (if present) would be toggled (Fig. 4.2).

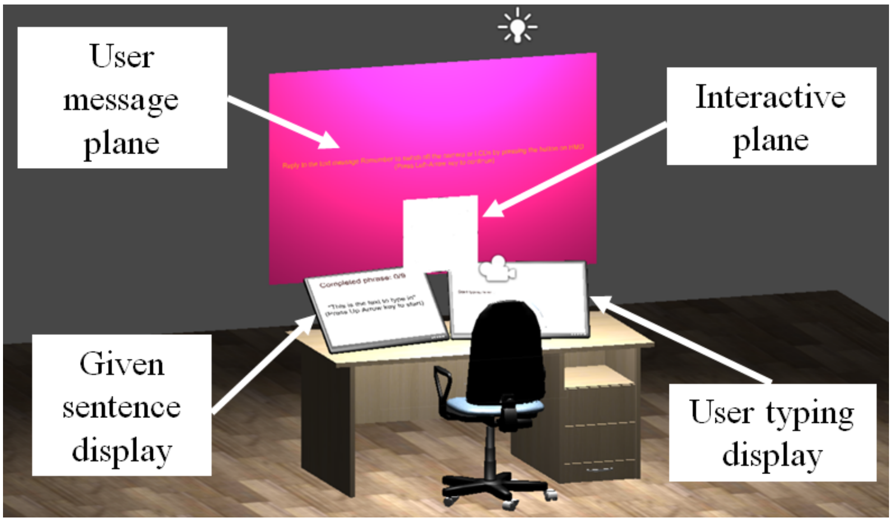

Figure 4.4: The virtual environment of the experiment.

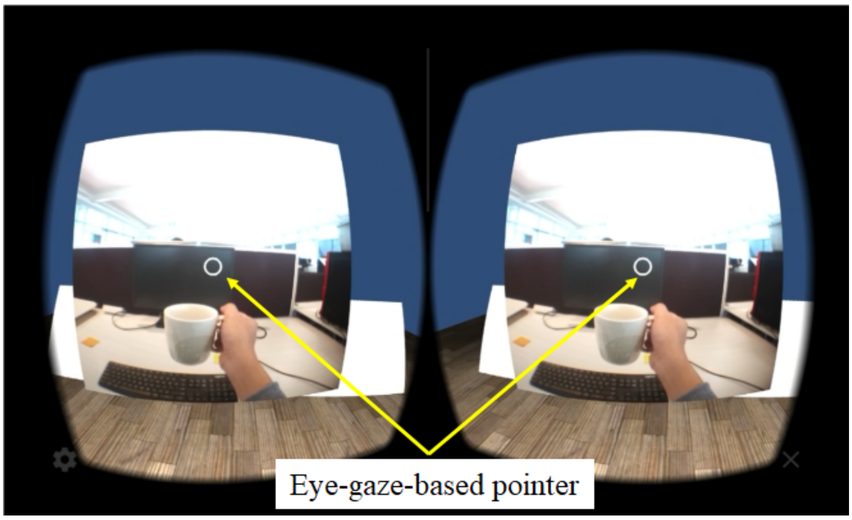

Figure 4.5: For MDI and VST, the subject used a head-controlled reticle and the buttons to select a targeted plane, and enable/disable camera stream viewing. When active, the stream would be shown to the subject on a large visual insert.

Tasks

VR Space: Each participant had to type nine phrases in VR. We randomly chose the phrases from a set of phrases based on the research of MacKenzie & Soukoreff [150]. After every three phrases, a message on the virtual message board prompted the subject to perform a RW task. The message contained clear instructions for carrying out the given task as described above. After the subjects completed the RW task, they had to return to the VR office, and close the message to continue with the virtual typing task.

RW Space: We designed the RW tasks around typical interactions with nearby objects in an office, such as responding to a phone call and jotting down the content on a sticky note, replying to a text message on a smartphone, and moving a mug on the desk. The subject had to pause the VR experience by either taking off the HMD or using visual channels when there was a RW activity required. For instance, using the MDI headset to interact with the smartphone for messaging, a user could find the phone, read the question, and type by looking at the rendered RW scene through the camera or by looking out through the bottom LCD panels. A virtual message board inside the VE (the purple coloured plane) displayed the task messages (see Figure 4.3). The messages were one of: (1) “Move the cup to the square B”; (2) “Take the smartphone, answer the phone call and write down information on the sticky note”; and (3) “Take the smartphone, and reply to the SMS”. We randomly located the mug’s position per task trial to prevent subjects from memorizing its location, as suggested in [19]. To initiate the Phone Answering and Text Messaging tasks, we used Google voice[5] to make a fake call or send a fake text to the phone using Fake Call[6]. Since our focus was on the reaction time and subjective feelings regarding the HMDs, the subject was free to respond whatever they wanted to their received texts [73, 173].

[5]https://translate.google.com/

[6]https://play.google.com/store/apps/details?id=com.fakecall.fakevideocall.prank&hl=en

4.2.3 Measures

We assessed the dependent variables using both objective and subjective methods. We measured the reaction time of each RW task per HMD condition and recorded the total task completion time per condition. We used validated questionnaires for the sense of presence, workload, and level of VR sickness as subjective measures. We chose the Igroup Presence Questionnaire (IPQ) to evaluate perceptions of both the virtual and real environments [149], and used a standardized Simulator Sickness Questionnaire (SSQ) to measure the level of VR sickness on a scale from 0 (none) to 3 (severe) [143]. For workload, we used the NASA Task Load Index (NASA TLX) questionnaire [48]. Finally, we created a set of post questions for comparison purposes among the HMDs in terms of "ease of control" and preference. To assess the subjects' behavioural responses, we recorded each session using an external web-camera.

4.2.4 Procedure

Before commencing the study, we asked each participant to read the information sheet and fill in and sign the consent form. We then gave a general explanation about the virtual and physical environments, the tasks in VR and the RW, and how to control the HMD (depending on the given condition). Before launching the application, we adjusted the HMD's IPD to match the participant. The participant then filled in demographic data and the SSQ using a laptop computer. Before running the experiment trials, we provided a practice session for each participant to become familiar with controlling the HMDs and understanding the tasks in the VR and RW. After completing the training session, we assigned the participant to one of the HMD conditions (chosen using a Latin square), and the subject pressed a designated key on the keyboard to start the experiment session after donning the HMD. We used the key-press time as the start time for recording the whole condition time. When the application started, the subject typed three phrases, then performed a RW task, then typed three more phrases in the VR again, then performed a RW task, then typed three more phrases in the VR one more time, then performed the last RW task. For each RW task, a message appeared on the VR message board and was read aloud to the experimenter. The experimenter then loaded in the proper material for the given task. The subject then filled in the IPQ, SSQ, and NASA TLX questionnaires after they completed each HMD condition. To avoid exhausting the subjects, we provided a short (passive) break between each HMD condition. After the subject completed all the conditions in this study, we provided a post-questionnaire. It took about one hour for a subject to complete all conditions.

4.2.5 Participants

We ran an F-test of "ANOVA repeated measures within factors" using G*Power 3.1.9.4, a target effect size of 0.8 and a power of 0.95 for three groups and five measures. The software suggested the sample size of six subjects. To increase the confidence, we recruited 20 voluntary participants using on-campus fliers at the University of Canterbury. We successfully conducted our experiment with 16 participants (age $M = 24.75$, $SD = 4.70$, eight male). Before running a session, we confirmed that the participants had normal or corrected-to-normal vision. Participants mostly had higher-education backgrounds and were studying diverse majors, mainly in computer science. All subjects were informed about the potential risk of VR sickness during the experiment and warned against driving or controlling heavy machinery for two hours afterwards (clearly stated in posters, flyers, and on social media recruiting posts).

4.3 Results

Initially, we recruited 20 participants, but we could not conduct the full experiment for four of these due to technical issues that resulted in the VE slowly spinning around the subject. We chose the non-parametric Kruskal-Wallis statistical method to analyze the data as our data was not fit a normal distribution. The raw data were captured from different sources, converted, and passed to SPSS for analyzing. The data for the RW task performance was extracted by analyzing the video footage to detect keyboard-

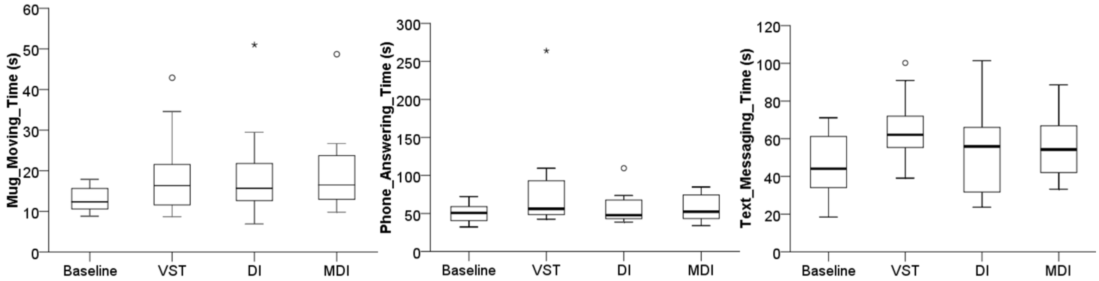

Figure 4.6: Performance (in seconds) of each task Mug Moving (left), Phone Answering (middle), and Text Messaging (right).

to-keyboard time, and physical object touching and releasing times. We extracted measurements for condition-completion times from the log files on the VR smartphone. The subjective data from questionnaires were captured and downloaded from our Qualtrics server. We used the scoring method from Igroup[7] and SSQ[8] to compute IPQ and SSQ scores, respectively. For the NASA-TLX questionnaires, we averaged the scores from all sub-questions to produce general workload scaling.

4.3.1 Task Time Duration

Each Time Duration started the moment the subject lifted their hand from the keyboard after receiving a particular RW task from the VR message board, and ended at the moment the subject put their hand back on the keyboard again. For the Mug Moving task, the subject needed to locate the mug, move it and place it on a designated location (Water mug endpoint in Fig. 4.3). A Kruskal-Wallis test showed that there were no significant differences of means ($\chi^2 = 6.197, p = 0.102$) (see Fig. 4.6, left). For the Phone Answering task, the subject had to write information received over the phone on a small notepad using a pen. A Kruskal-Wallis test showed that there were no significant differences of means ($\chi^2 = 4.890, p = 0.180$) (see Fig. 4.6, middle). For the Text Messaging task, the subject had to unlock the phone, find a newly-arrived text message, read the content, and answer by typing back. A Kruskal-Wallis test showed that there were no significant differences of means ($\chi^2 = 6.160, p = 0.104$) (see Fig. 4.6, right).

[7]http://www.igroup.org/pq/ipq/data.php
[8]http://www.cybersickness.org/Simulator_Sickness_Questionnaire.htm

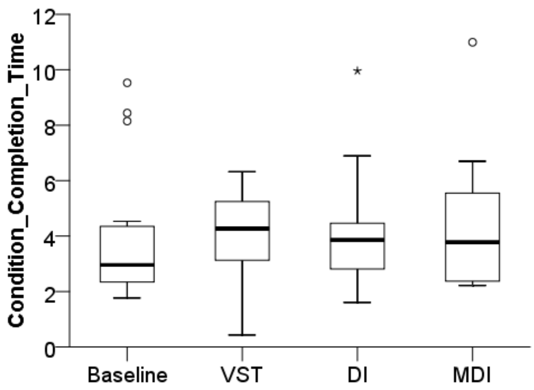

Figure 4.7: A comparison of time (in minutes) for each experimental condition to be completed.

For the total condition time for a given condition, a Kruskal-Wallis test showed that there were no significant differences of means ($\chi^2 = 2.253, p = 0.522$) (see Fig. 4.7).

4.3.2 Effective Working Duration

In this section, we look more closely at the portion of the total time spent actually touching the target physical objects in the RW tasks (starting from the moment of touching to the moment of releasing the smartphone and mug). We extracted these times from the captured videos using the web-camera. We then calculated the portion of the Task Time Duration (previously obtained data) spent in contact and in transition to get effective duration data, and ratios in percentages. As shown in Table 4.1, in the Mug Moving

Table 4.1: Descriptive statistics to show portions of time actually touching the RW objects over keyboard-to-keyboard times for tasks, Mean (Standard Deviation)

	Task Time Duration	Touch Duration	Transition Time	Ratio (%task / %transition)
Task 1: Mug Moving				
Baseline	12.89 (2.87)	1.47 (0.48)	11.43 (2.84)	11% / 89%
VST	18.56 (9.14)	3.23 (1.10)	15.33 (8.70)	17% / 83%
DI	18.52 (11.07)	2.41 (0.72)	15.25 (11.53)	13% / 87%
MDI	19.59 (9.77)	3.16 (1.11)	16.43 (9.59)	16% / 84%
Task 2: Phone Answering				
Baseline	51.14 (12.02)	28.35 (5.72)	22.79 (12.09)	55% / 45%
VST	78.31 (54.25)	33.16 (12.73)	45.14 (55.84)	42% / 58%
DI	55.61 (18.55)	30.51 (5.06)	25.10 (18.16)	55% / 45%
MDI	57.84 (17.49)	34.45 (10.77)	23.39 (13.42)	60% / 40%
Task 3: Text Messaging				
Baseline	46.71 (16.61)	22.46 (9.92)	24.25 (14.08)	48% / 52%
VST	64.39 (17.91)	46.2 (14.03)	17.06 (20.75)	72% / 28%
DI	53.24 (21.89)	28.48 (9.86)	24.77 (19.33)	53% / 47%
MDI	56.89 (18.71)	40.21 (18.71)	15.64 (18.14)	71% / 29%

task, 80% of the time was for transitioning, while the amount of time handling the mug only accounted for less than 20% of the time. Among the conditions, there was not much difference. For the Phone Answering task, the amount of time spent on transitioning was generally less (40-60%) than the time for accomplishing the task for most of the HMD types. The exception was VST, where we saw a high standard deviation for the total time, probably due to technical issues. For the Text Messaging task, we can see that Baseline and DI resulted in more significant transition proportions, while VST and MDI showed a more efficient rate for the actual object interacting times.

4.3.3 NASA-TLX

We used NASA-TLX to measure the general workload of the subjects, with no separation within the questionnaire about RW or VR tasks. The results are means taken from the six questions, and no weighting factor was used. Higher values correspond to higher perceived workload while doing the tasks. A Kruskal-Wallis test showed that there were no significant differences of means ($\chi^2 = 4.148, p = 0.246$) (see Fig. 4.8) for the HMD types.

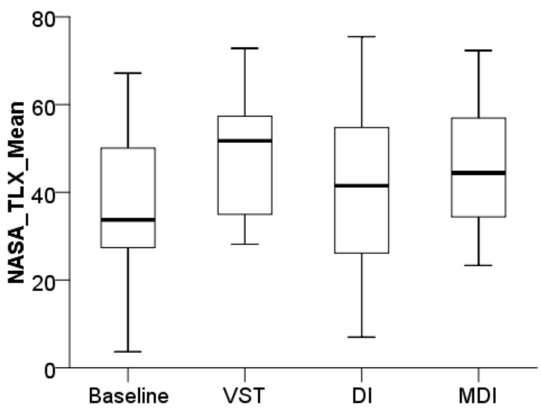

Figure 4.8: The average NASA-TLX workload.

4.3.4 User Preference

We surveyed the "ease of use" feeling and "device preference" for the experimental devices at the very end of the experiment. Higher numbers represent higher preference (number of subjects who selected a particular device).

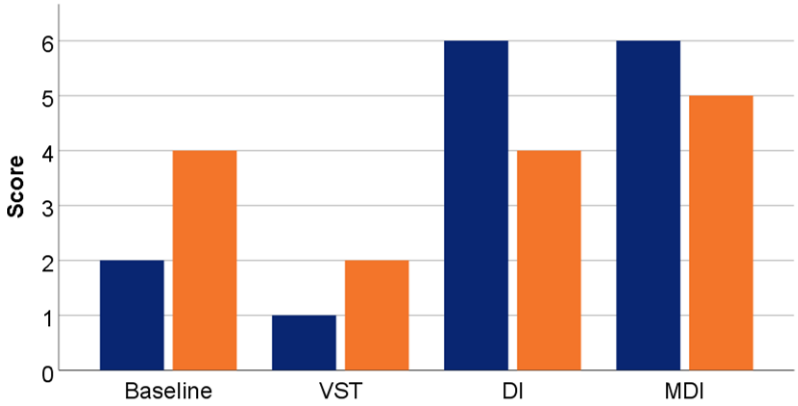

Figure 4.9: The combined scores for ease of use (dark blue) and preferred to use (orange) for the four conditions.

Among the four HMDs, the subjects seemed to vote for both MDI and DI equally in terms of how easy it was to use, over Baseline and VST (see Fig. 4.9). When asked to choose one of the devices for use in the future, most subjects rated the MDI, then DI and Baseline, then VST.

A chi-squared goodness-of-fit test indicated there was a marginally significant difference ($\chi^2(3, n = 16) = 6.5, p = 0.09$) in the rated ease of use of the devices (Baseline: 12.5%, VST: 6.3%, DI: 37.5%, MDI: 43.8%). The differences between device preference were not significant ($p = 0.572$).

A further analysis comparing the MDI and DI HMDs with the generic display by collapsing the ratings of each of their categories shows a strong and significantly higher ($\chi^2(1, n = 16) = 6.25, p = 0.012$) ease of use rating for the DI devices (DI devices: 81.3%, Baseline HMD: 18.8%). The comparison between preferences was not significant ($p = 0.317$).

Subjects also gave comments about their experience in terms of devices and technologies. For the devices, we only found responses related to the Baseline and MDI devices from the comments.

"The Generic HMD has the best VR experience as long as you don't need to interact with the real world frequently..."

"...I found it just as easy most of the time to lift the headset or take it off."

"...MDI is much better than using fish-eye or DI independently on interacting with the real world..."

"...I think the headset which is combined with both a camera and LCD panels helps users to do something easily..."

In terms of technology, users gave feedback about their experience. In using DI technology, users reported some negative experiences:

"...forced you to roll your eyeball and it was not a pleasant experience..."

"...reduced the feeling of being in the world..."

Other users saw DI as useful:

"...felt more comfortable to use than the video see through as it seemed to achieve the perfect balance between virtual reality and reality..."

"LCD panels were easy to use."

"...The LCDs were also higher visibility, especially when viewing the phone screen"

When wearing the camera-based HMDs (VST and MDI), the participants reported several limitations of this technology:

"...fish eye reduces my physical sense of my body..."

"...the camera was also very blurry..."

"The camera had a different perspective from the LCD lenses and felt more zoomed-out"

"...the exposure of the camera made it quite hard to see..."

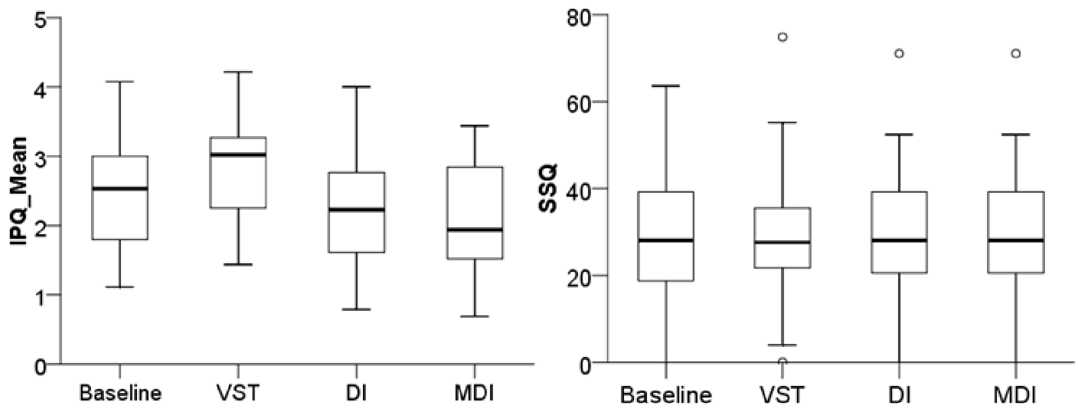

Figure 4.10: The average IPQ scores (left) and the induced levels of VR sickness (right).

4.3.5 IPQ

For estimating the depth of the presence, we used the IPQ. Since all four properties of the IPQ (General presence, Spatial presence, Realism, Involvement) resulted in similar patterns, we show the total mean scores for all factors and show the total results in Fig. 4.10, left. Higher values correspond to a deeper sense of presence in the VE. A Kruskal-Wallis test showed that there was no significant difference in means ($\chi^2 = 6.599, p = 0.086$).

4.3.6 SSQ

VR sickness symptoms present during each condition were measured using the SSQ. It is important to note that we also captured the sickness state of each subject with a pre-experiment SSQ. We then compared all the post-condition questionnaires to this one. Higher values correspond to more feelings of sickness during a particular condition. No participants dropped out of the experiment due to simulator sickness. A Kruskal-Wallis test showed there were no significant differences of means ($\chi^2 = 0.082, p = 0.994$) (see Fig. 4.10, right) in terms of HMD types.

4.4 Discussion and Future Work

In this experiment, we did not find general support for our research hypotheses in terms of presence and VR sickness, but we partially supported the usability hypothesis, which showed some benefits of MDI. In support of hypothesis H4.1, we found a trend that the subjects chose the MDI HMD as their preferred headset during this experiment, with the DI and the generic HMD next, while the VST HMD was the lowest among the HMDs. Similarly, the MDI and DI showed the highest ratings of ease of control, whereas the VST was the lowest among the HMDs again. However, we did not find a significant difference in the objective measurement result from the subjects in moving a mug, responding to a phone call, or replying to a text, nor in the total task completion time for each condition. The subjective questionnaire responses also did not show any significant differences in terms of workload. Regarding H4.2 for the sense of presence and H4.3 for VR sickness, the IPQ and SSQ questionnaires comparison resulted in no significant differences to verify those hypotheses.

Furthermore, we found that the general idea of providing multiple visual channels to an HMD was positive for the RW activities using a simple switching method, but we should improve the quality of the integrated components and the usability. For example, looking at the recorded video, the MDI and VST HMDs provided more comfortable postures for the note-taking task, and we conjecture that the wide-angle fish-eye lenses helped to quickly find the location of the notepad and pen, which were placed at a far distance relatively speaking. Similarly, participants seemed keen to use the MDI and DI HMDs for handheld device tasks (texting on a smartphone), and we assume the LCD panels helped to search for the nearby phone and provided enough vision to work with the phone effectively because it could be moved near the LCD panels.

The data collection and scenario logic need to be improved. For the experiment, the implementation of keyboard typing needs more optimization. The HMD should have more convenient support for users to glance at the keyboard while typing. There should also have been a typing performance metric. In the experiment, the VE prompted the users with instructions to perform tasks. This implementation seemed to break the reality of the task. Thus, the notifications for RW events should come outside-in instead of inside-out in a random manner.

We also found some technical limitations for MDI related to the video and optical components. First, the fish-eye lens had distortion and low resolution, was sensitive to light exposure, and the rendered video in the VR space was not an optimal size compared to the VE and FOV, so subjects may not have been able to use the video rendering efficiently. Since we used a mobile-VR based platform, the camera resolution and location were a limitation, including a lack of depth information. This limitation prevented the VST or MDI HMD from rendering the real scene at a proper distance from the user's eyes. The other drawback was that the placement of the camera restricted the viewing angle of users. The fish-eye lens helped subjects to see with a broader view angle, but it did not solve other problems that constrained the view. We did not scale the fish-eye lens scenes to our flat 2D plane, which led to a minor inconvenience due to a distortion in seeing the RW. We have since found an undistortion process that can be done quickly in Unity with a curved plane. The LCD panels worked well in terms of seeing the outside world by glancing and provided good light blockage for immersion in VR when closed. However, the LCD panels need to be bigger to expose more extensive areas, since the HMD nose bridge blocks the middle of the bottom area. To fix this, we can redesign the shape of the LCD panels to give maximal expansion and avoid discontinuity in the RW view due to eye separation. Lastly, the other major problem was caused by drift issues with the inertial sensors in the mobile VR platform while participants were experiencing the MDI, DI, and VST HMDs. We expect that the problem can be resolved with an optimization of the software or moving the implementation to a desktop platform.

4.5 Chapter Summary

In this chapter, we proposed a Multi-channel Dynamic Immersion (MDI) headset, which effectively supports RW activities while the user is wearing an HMD (regarding research question 2). The new HMD is based on a mobile-VR headset and a combination of DI (peripheral view) and VST (centre view) visual technologies. The users experienced wearing a customized HMD and performed different types of interactions with different objects on the table in front of them, including keyboard, smartphone (texting, answering), cup (moving), and taking notes with pen and sticky-note without having to leave their HMD. With data from 16 participants (after four dropouts), we evaluated the usability of MDI compared to the previously-proposed solutions for usability, the immersion level, and VR sickness. We exposed some of the advantages and disadvantages of the various HMD types and their potential use in VR, though we could not find support for our stated hypotheses. The participants chose the MDI as their preferred HMD when required to interact with nearby physical objects and rated the MDI HMD for significantly high ease of use. Thus, we believe the MDI HMD could be an option for improving long-duration usage of VR.

Thus, there is a need to improve both VST and DI technologies to enhance the general MDI experience based on our findings (removing distortion, improving comfort for the nose bridge, and drifting issues). In addition, a crucial next step is to migrate the technological implementations onto a more stable platform with a systematic and adaptive design. The new system should offer different ways of control from manual to voice commands. We will also add support for the audio channel, and for VR user to non-VR user interactions in VR. We discuss these and further enhancements in more detail in the next chapter.

Chapter 5

Workspace-VR HMD System

In the previous chapter, we investigated the impact of an MDI HMD in terms of usability, immersion and VR sickness. The device used VST and DI technologies to provide a wide-FOV visual channel to access the RW. Our test found that the VR users somewhat preferred the MDI HMD over other systems. However, there were some limitations in both the implementation of the two technologies and the platform used. To address these drawbacks, in this chapter we introduce a Workspace-VR HMD system. Based on MDI, we enhanced the viewing channels and added a sound channel to support natural conversations between the VR user and non-VR interlocuters. We then developed a study design to evaluate the newly designed HMD system in terms of user experience, user well-being and user preferences for all related actors. The user study was reviewed and approved by the University's Human Ethics Committee (Application number: 2020/30/LR-PS; see Appendices C and D for relevant documents). However, due to the outbreak of the COVID-19 pandemic, we were not able to actually conduct the user study.

5.1 Introduction

In the previous chapter, we investigated the fundamental problem for an immersed HMD user of its limitation in allowing interaction with nearby objects [19, 41, 106]. Over and above reaching objects, however, a VR user also needs to maintain situation awareness [44], but the visual/audio isolation when using a conventional HMD reduces the sense of being with other people, and conversely also leads to awkwardness for people in the RW when wanting to talk with the VR user.

We partially addressed this problem in the previous chapter with our investigation of the MDI HMD. The HMD employed two visual technologies to cover both frontal and peripheral view for the user to access their physical world without having to leave their HMD, and with smooth transitions. Our user study showed that the subjects tended to prefer the use of this HMD for their allocated tasks for object interactions. More, both the VST and DI technologies showed different advantages for different types of interactions when using different objects. However, the HMD had limitations in the installation of the LCD panels for the DI technologies, which caused a nose bridge problem when the users' eyes could not focus together when looking out of the bottom LCD panels. During the experiment, the subjects also experienced an issue with uncontrollable rotations of the VE (drifting) due to problems with the sensory tracking system on the smartphone. A further limitation of our prototype was that the MDI HMD was designed to be a standalone HMD with limited performance and had no generic design to adapt to any other HMD platforms. Additionally, it was not sufficiently robust for large-scale usage with a higher degree of control and monitoring.

In this chapter, we present an advanced HMD system from the MDI HMD, which we call *Workspace-VR*. The Workspace-VR HMD system is the migration of the VST and DI visual technologies onto a stable HMD platform, HTC Vive. With this HMD, we aim for optimizing the use of the DI technology in parallel with the use of the HTC Vive's built-in camera for the VST technology. We also explore the sound channel with the implementation of Hear-through AR (HTAR) [96] for the audio technology due to its naturalness of hearing, although Mic-through AR (MTAR) technology [95] is also a promising candidate. To support the non-VR person in conversations with the HMD-wearing VR user, we propose the use of an Emotion Display component to provide eye contact cues on the front of the HMD. In addition to that, we also study the potential of reducing VR sickness using DI technology from its naturalness of using LCD glasses to let in the RW [94], thereby providing grounding cues. We designed the new HMD with a Client-Server based model for supporting scalability and used 3D printing technology for a replacement part for DI technology and Emotion Display on the Vive. We then developed a user study for testing the new HMD system for both user preference in general and on particular components, as well as assessing their keyboard typing performance.

5.2 Methods

5.2.1 Research Questions and Hypotheses

To provide a more convenient VR workplace experience to all related VR and non-VR users, we upgraded and optimized the features of the previous HMD onto the Workspace-VR HMD system. The Workspace-VR HMD has the addition of new HTAR sound technology along with a newly-proposed Emotion Display to support more-natural engagement for face-to-face communication for the non-VR user. Therefore, our research question is: How well can the new HMD system overcome the limitations of the previous MDI HMD to enhance user experience and support VR-to-non-VR user communication? Thus, we are investigating the improved visual channels, automation, sound and eye contact. We then formulated four hypotheses to guide and evaluate our work, based on previous related work (see Chapter 2):

- **H5.1**: Workspace-VR will provide a high score for user experience.
- **H5.2**: Workspace-VR will allow users to maintain a comparable level of visual comfort after the VR experience compared to pre-experiment measurements.

- **H5.3**: Workspace-VR will allow users to use a keyboard at a similar level of proficiency as they normally would.

- **H5.4**: Workspace-VR users will consider the application of the Emotion Display, HTAR, DI, and VST technologies as helpful, as measured in their preference ratings.

5.2.2 User Study Design: Explanation of the Process

We planned to run the user study described below, and received approval for the study design from the University of Canterbury Human Ethics Committee (Application number: 2020/30/LR-PS). However, due to the national COVID-19 lock-down, we had no access to the necessary facilities and participant recruitment pool. Instead of waiting, we decided to shift the thesis writing forward with a detailed report of the work and user study design. We plan to run a full user study and in-person evaluation after the submission of this thesis, as soon as social distancing requirements permit.

User Study Design

The experiment will be based on a within-subjects design. Along with having the Workspace-VR as the apparatus, we have defined several dependent variables to evaluate the HMD system, including the UEQ and CVSQ, objective keyboard performance, and user preferences. We will manage the participants by pairs. In session 1, partner A will experience the system for interacting with objects for office tasks and having a typical conversation with a colleague, while partner B plays the role of the colleague to experience the supported eye contact (Emotion Display) component. In session 2, they will swap roles. We ran a G*power analysis for a t-test to find the difference between two different means (matched pairs) with an effect size of 0.8 to obtain a recommended sample size of 20 participants. The experiment is expected to take approximately 1 hour and 30 minutes.

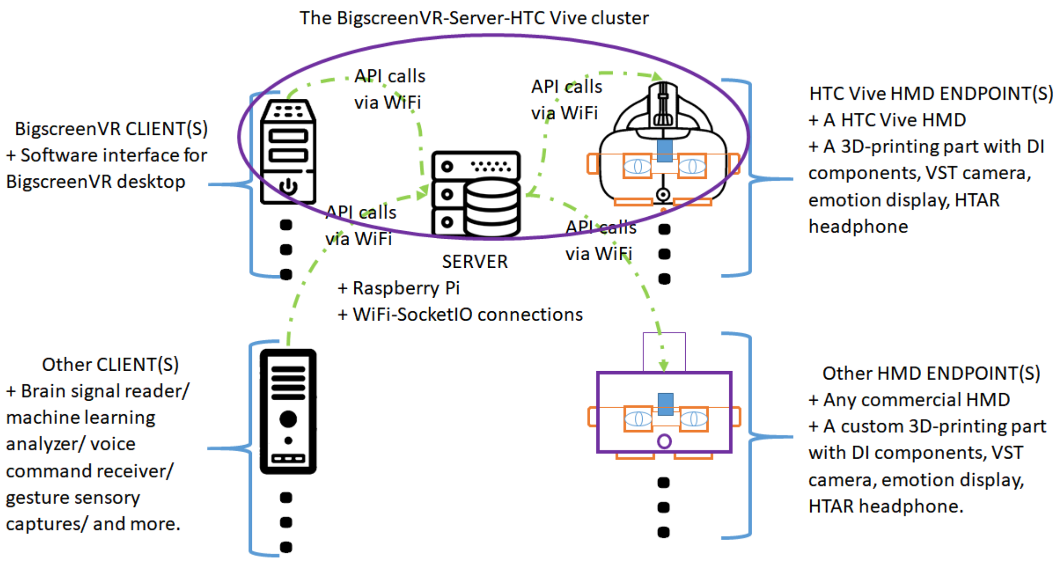

Figure 5.1: The architecture of the Workspace-VR system including suggested clients (left side of the Server, possible variations of endpoint subsystems to match with different HMD designs (right side of the Server, and the current implemented cluster.

5.2.3 Materials

System Architecture

The Workspace-VR HMD system is centred around a **Server** with multiple heterogeneous clusters (see Fig. 5.1). A **Cluster** contains a **Client** and an **Endpoint**. The overall architecture of the system allows expansion to large scale implementation. The Clients can vary, such as BigscreenVR clients for the implemented HTC Vive based version, or even more complex processors like voice commands, a Brain-Computer Interface (BCI), or a machine leaning analyzer, etc. The Endpoints are different replacement parts to fit different HMD designs. A Client and an Endpoint only communicate with each other via the Server. Generally, the Server can handle multiple Clusters at a time, up to the upper limit of a WiFi network connectivity. In this particular study, we will only use the cluster of **BigscreenVR Client-Server-HTC Vive Endpoint** (as indicated), with further understanding about the communication between components described below.

The Server uses a Raspberry Pi[1] 2 Model B V1.2 2014 with 16GB external storage, and runs a Raspbian operating system. To connect with the local network, the Server board uses an ASUS USB WiFi dongle[2]. In the enabled cluster, the Client is the Workspace-VR software interface (in C#), and the Endpoint is a combination of a Huzzah board from Ada-fruit as the controller/wireless module and two OLED Microview[3] displays for the Emotion Display (both in Arduino C++).

The Server is responsible for translating, multiplexing, and relaying the messages from the Clients to the Endpoints. For management purposes, the Server handles two tables (called *system images*) of connected Clients and Endpoints. For Clients, each connected instance is an object with an ID, socket ID, and IP address. The Server also has a list of connected Endpoints, each with its ID, Socket ID, IP address, connected port, the left side LCD (LCD_Left), middle bottom LCD (LCD_Middle), and right side LCD (LCD_Right)'s transparency level. However, in this work, we enable only the two bottom LCD panels.

In this scheme, the Client-Server-Endpoint connectivity follows SocketIO conventions for real-time bidirectional, event-based communication. The base of this communication technology is the passing of messages with an event name and payload, and an optional acknowledgment mechanism. We define multiple Event names for our architecture in fixed 11-character-length instances, for instance "CLI_SET_FAS" or "CLI_GET_ALL" (see Figs. 5.2 and 5.3). The events are mainly for "Set" and "Get" purposes and exist in different forms for different communication purposes. The "Set" event set helps to drive either the LCD levels or control the Emotion Display. In this category, we divide these into uni-cast (to give commands to only one target Endpoint), multi-cast (giving commands to a specific range of connected Endpoints) and broadcast (give commands to all connected Endpoints). For the "Get" event series, the Client can ask for the status of a specific Endpoint or look for a full system image of connected Endpoints. In terms of the payload part for each event call, this portion is in a

[1] https://www.adafruit.com/product/2358
[2] https://www.asus.com/me-ar/Networking/WL167g/ProductPrint/
[2] https://www.adafruit.com/product/2471
[3] https://www.sparkfun.com/products/12923

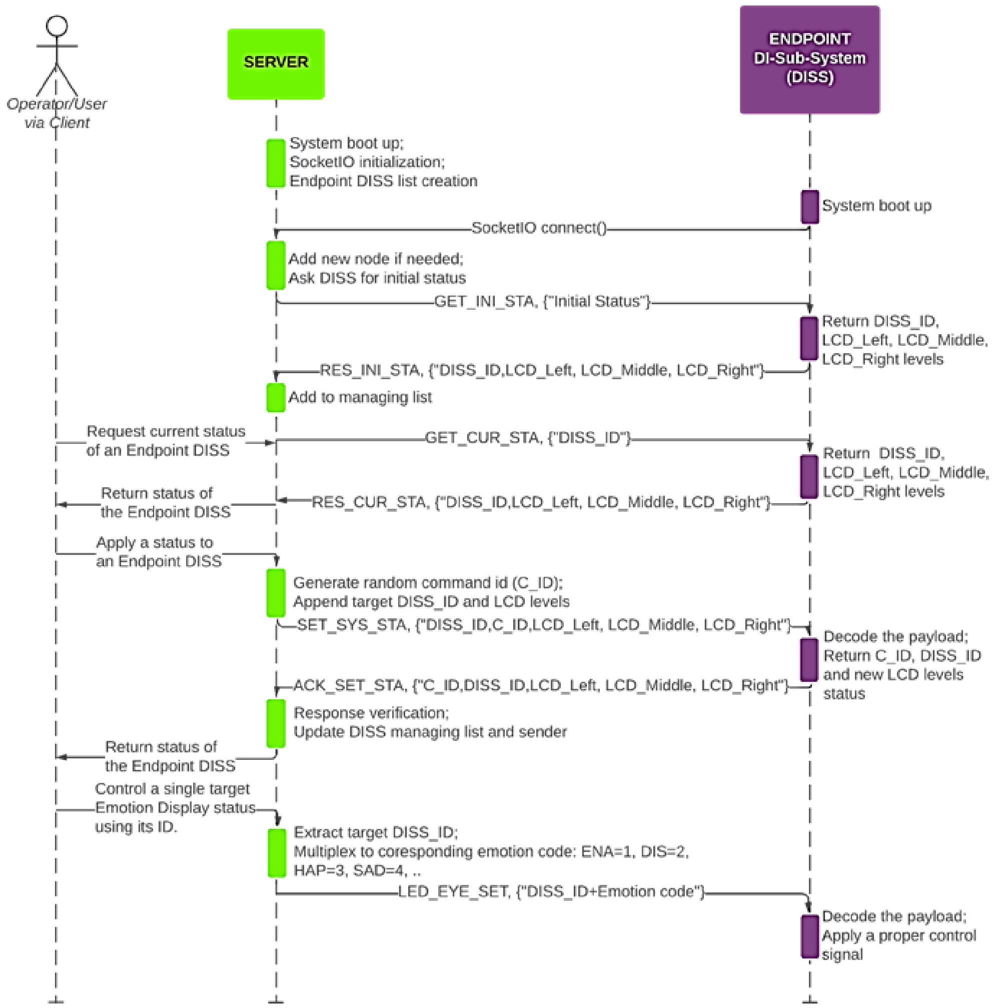

Figure 5.2: The sequential diagram for the Server-Endpoint event data communication.

determined format for the “Set” event series and uni-cast “Get” events.

To control the LCD levels for an Endpoint, the Client gives simple information, including the fields of Endpoint ID (7 bytes), C_ID (1 byte), LCD_Left level (1 byte), LCD_Middle level (1 byte), and LCD_Right level (1 byte), with a comma delimiter ’,’ between each field. The ID field is a unique identification of a Client (CLIENT_ID) or an Endpoint (DISS_ID) when it connects to the Server. The C_ID (Command ID) field is for managing in larger scenarios where the Server has to give multiple commands to multiple Endpoints. The Server has to acknowledge its given commands to ensure that they are in the desired execution order (as received from multiple Endpoints) then update its managed system table.

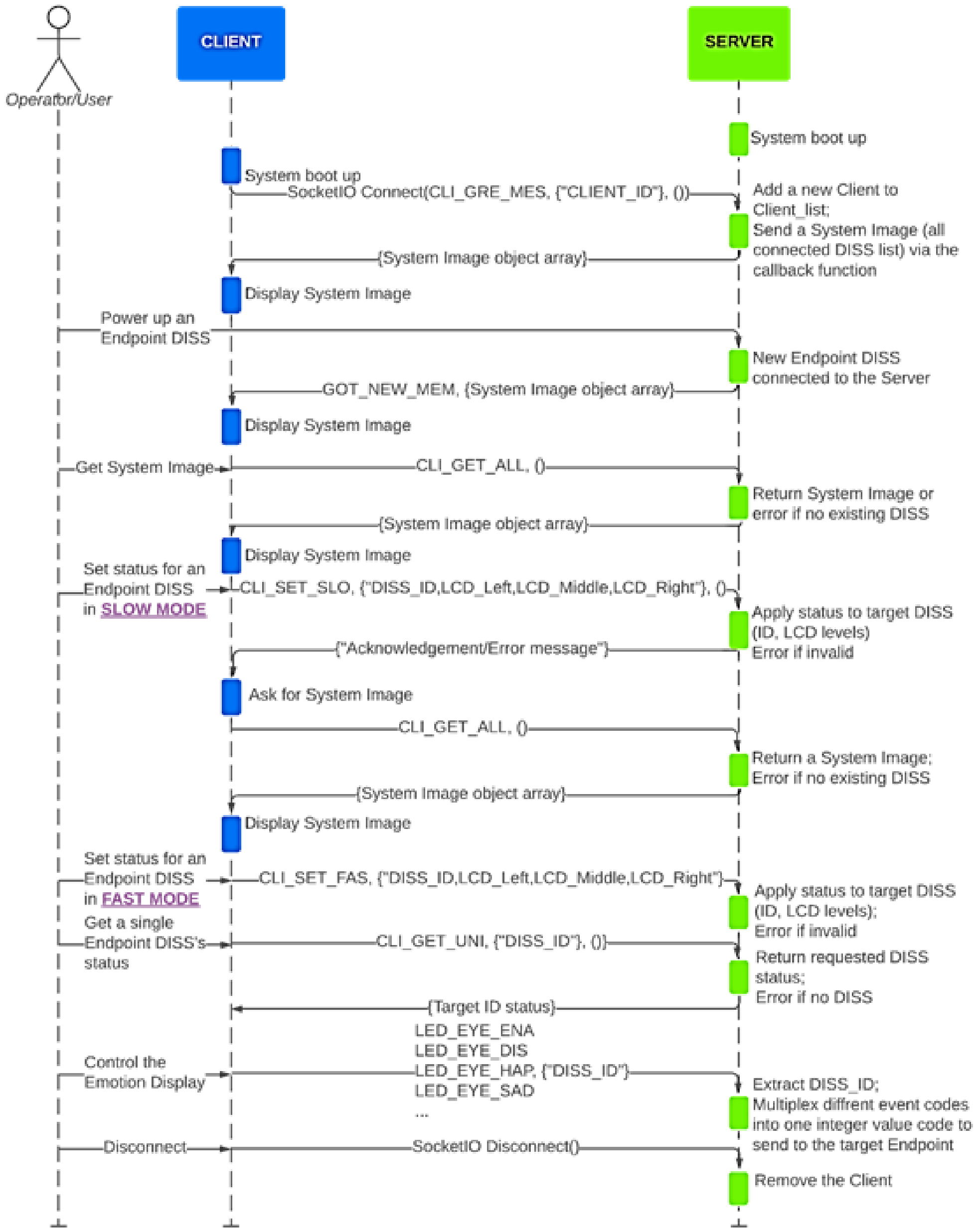

Figure 5.3: The sequential diagram for SocketIO-formatted exchange data.

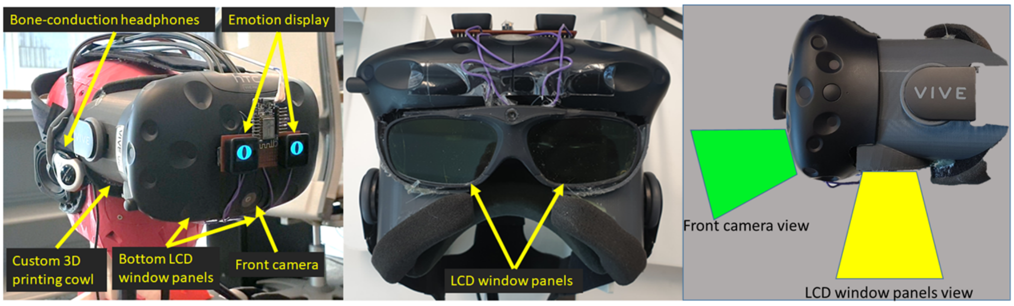

Figure 5.4: The modified HTC Vive HMD with two micro-view displays of the eyes (in blue color) and the built-in camera on the front, and bone-conduction headphones (Left). The bottom contains the controllable LCD panels attached onto a custom-designed 3D printed cowl (Middle). The VR user can look to the RW with two viewing channels from the front camera or bottom LCD panel windows (Right).

To control the Emotion Display, the Client can send a package with Endpoint ID (7 bytes) and an Emotion code (1 byte). The Emotion codes include numeric payload with "1" enable, "2" disable, and more options for future development. We do not apply a C_ID mechanism for exchanging data from/to the Emotion Display to reduce communication traffic. For a broadcast-based "Get" event, the Client tells the Server to return its managed system images. In this event, the payload size depends on the Server's current table sizes.

The SocketIO networking library also provides a blocking message transmission with a wait for an acknowledgment message from the receiver. Thus, we have both a slower, but more-reliable, and faster, but less-reliable, mode for command execution by enabling/disabling the feature. Besides, to enable the voice command and video feed for the Workspace-VR software interface, we use Microsoft Speech Engine with a predefined dictionary of keywords for controlling the system and AForge[4] dynamic library to handle video-feed rendering.

Apparatus

Workspace-VR HMD system with an Emotion Display: The HMD for Workspace-VR is a highly modified HTC Vive Pre[5] with much of the plastic cowl surrounding the

[4]http://www.aforgenet.com/framework/
[5]https://www.vive.com/nz/product/vive/

headset replaced with our technology (see Fig. 5.4). For the parts, we used the LCD panels from a pair of Acer DLP 3D E4W active 3D shutter glasses[6] with a viewing angle of 60 degrees, operating frequency from 96 to 144 Hz, an ON response time of 0.6ms, and OFF response time of 2.6ms, and a contrast of 1200:1. The LCD panels were placed at the bottom of the HMD to cover the viewing area when the user glances down. We custom 3D printed a cowl to hold the LCD panels that mates with the original Vive lens assembly and head-strap anchors. This cowl is the only replacement part, though we had to cut away a small portion of the Vive front shield so as not to block the LCD panels. The rest of the Vive components remain unchanged.

For sound, we used HTAR [96], including the AudioBone[7] bone-conduction headset. For capturing the front-view, we took advantage of the HTC Vive's built-in camera due to its proper capturing angle and to avoid the additional weight, although the resolution is limited to 640x480 pixels and difficult to outfit with a fish-eye lens. In addition to clicking virtual buttons in the VR, we capture voice commands from the user via the Vive's built-in microphone, and pass it to the Microsoft Speech Engine[8] for the user to control the system. To display an eye-pair on the HMD, we installed two 64x48 pixels OLED Micro-View displays. The Emotion Display draws two identical and simplified eyes and performs simple animations of blinks with two animation frames, and blink at a 0.5-second rate. These displays are connected in series and share power with the WiFi transceiver module (Huzzah board). This Huzzah board is also the main controller of both the Emotion Display and LCD panels. The module works at an 80Hz frequency and contains both digital pins to control the Emotion Display and Pulse Width Modulation pins for varying the transparency of the LCD panels. The module handles the SocketIO library for establishing and managing wireless connectivity and powered by the USB 3.0 port on the Vive. Overall, the replacement components weigh 130g, which leads to a total weight for the modified HMD of 585g, only slightly heavier than the unmodified Vive at 528g.

Physical Environment: The main design of the user study involves a basic office

[6]https://www.acer.com/ac/en/ID/content/support-product/7112;-;
[7]http://www.goldendance.co.jp/English/product/p_ab01.html
[8]https://www.microsoft.com/en-us/download/details.aspx?id=27224

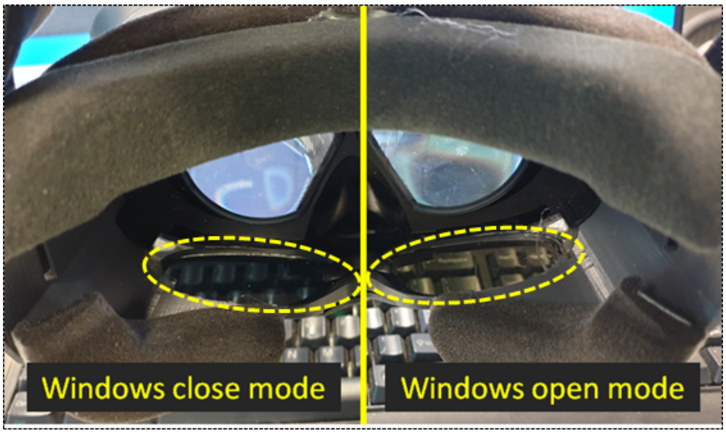

Figure 5.5: The LCD panels in different modes of light blocking (left), and see through (right).

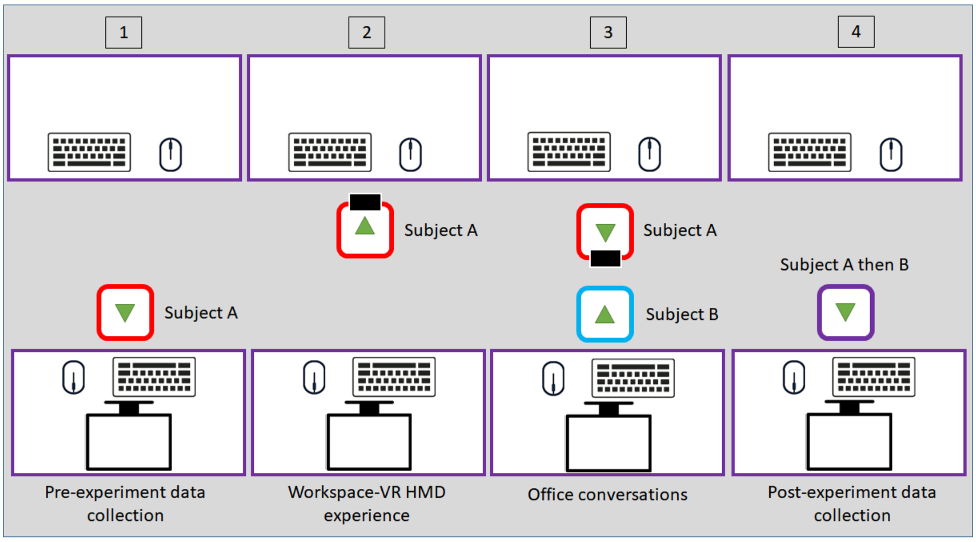

Figure 5.6: The four phrases in the physical set up of the experiment.

setting. It spans four phases (Fig. 5.6): pre-experiment data collection, Workspace-VR HMD user experience, conversation experience between pairs of users, and post-experiment questionnaires for both users. The physical environment of the experiment centres around the VR user sitting in a swivel chair at a desk with a keyboard, mouse, and VR HMD. Behind the subject is a traditional workstation where a non-VR "colleague" sits at a PC with a monitor, keyboard, and mouse. Apart from the HMD, both stations have the same dimensions, devices, and items. The VR user is the primary user of the system's features, while the colleague experiences in-person communication through the Emotion Display.

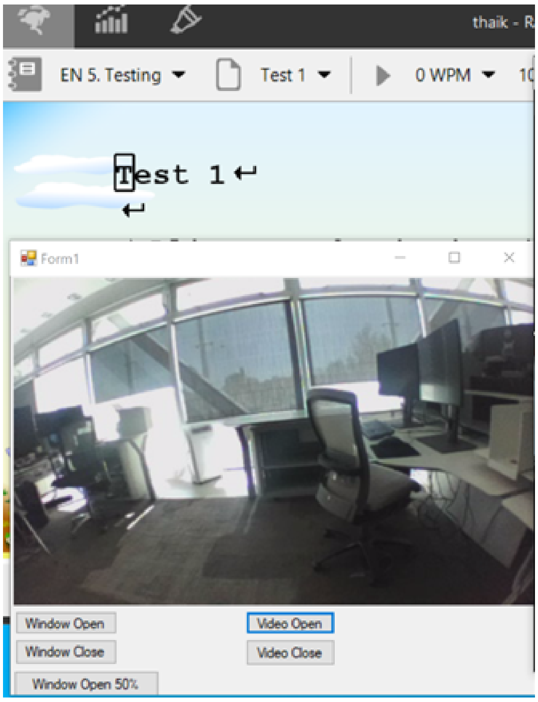

Figure 5.7: The software interface renders the video feed when the user enables the camera view.

Virtual Environment and Software Interface: We use an existing free VR environment from Steam, BigsreenVR[9], for our design. BigscreenVR is an application which allows VR users to see their PC's desktop screen on huge virtual monitors in the VE along with different virtual spaces to customize. The software requires an HTC Vive controller for initial settings before being independently managed by only the keyboard and mouse. We enlarge the 2D desktop by 225% for the text to be easier to read in the VR desktop of the BigscreenVR application. In addition, we set the desktop screen to be head-fixed to allow the user to see the video feed from the software interface on the VR desktop regardless of the chair rotation. If the desktop is world-fixed, the screen will stay still and the user will have to rotate to see the desktop and video; if the user turned too far from the desktop, they would not be able to see the applications any more. On the VR desktop application, the user can only interact with our typing software, browse movies from our library, and use the software interface for accessing the system features while doing the assigned tasks. Note that the user can either use voice commands or click buttons to manipulate the Workspace-VR specific features (e,g., LCD panels).

[9]https://www.bigscreenvr.com/

The software interface is a standalone application that captures voice commands, has buttons for controlling Workspace-VR features using the mouse, and a dedicated area to display the VST video (see Fig. 5.7). The "voice commands" and corresponding [button]s include:

- **"Window open"/[Window open]**: Set the LCD panels for near-field object interaction at 100% transparency
- **"Window fifty"/[Window 50%]**: Set panels to 50% transparency
- **"Window close"/[Window close]**: Set panels to 0% transparency
- **"Video open"/[Video open]**: Activate front-camera video feed
- **"Video close"/[Video close]**: Deactivate front-camera video feed

The LCD panels' stages include light-blocking (Fig. 5.5, left) and see-through (Fig. 5.5, right). The "video open" mode shows a video feed captured and rendered on the software interface (Fig. 5.7).

Scripted Conversation Questions: The study will include two conversations between the VR user and non-VR user in pairs, one with the Emotion Display, and one without (counterbalanced). While we give the VR users freedom to give their own responses, we script simple questions for the non-VR users to ask. The conversational questions will be selected from the NUS SMS Corpus [173] with two questions per conversation.

Measures

In this section, we present our approach to collecting and processing subject data. We will use questionnaires, including the UEQ, CVSQ (pre- and post-experiment), as well as preference questions for the VR user, and simple custom preference questions for the non-VR user. All the questionnaires will be deployed and collected through a Qualtrics web-based survey.

User Experience: We will evaluate the user experience of our system using the User Experience Questionnaire (UEQ) [88]. This questionnaire will assess not only the usability, effectiveness, and efficiency, but also the quality and user satisfaction. We will deploy the questionnaire using the University's online Qualtrics platform, and then use the benchmark technique [148] to assess the levels of user experience: Excellent, Good, Above average, Below average, and Bad.

Visual Fatigue: We want to measure the visual health of the user after the use of the system and investigate the potential of the DI technology in visual fatigue reduction as Lindeman et al. proposed [94]. We selected the subjective measures from the Computer Vision Syndrome Questionnaire (CVSQ) [152] because its symptom items are clear descriptions of eye fatigue symptoms, and also it is quick and easy to gather subjective responses on a computer. We will survey subjects with the CVSQ before and after their VR session. The CVSQ will also be delivered using Qualtrics and later exported to a ".csv" file to use in SPSS software for data analysis. We will then use a paired-samples t-test to assess the visual health of the user if there are any significant differences between the before and after scores.

Keyboard Typing Performance: We aim to evaluate the efficiency of the Workspace-VR HMD system objectively by using keyboard typing performance (as part of object interactions) using free Rapid-Typing software[10]. In the software, we will use its predefined 10-minute tests. After the user finishes a test, we will extract the performance data (words-per-minute) from the software. The typing performance will be captured at two instances initially on a standard desktop and then via using the Workspace-VR. The data analysis will involve the paired-samples t-test to compare the typing performance on the PC and the new system.

VR User Preferences: We will also evaluate the VR user's preference for the HTAR headphones, DI and VST technologies. We will use a custom question set for this purpose (see below). Then, a simple summation reporting approach will be used to assess the data regarding the preference in near-object interactions and face-to-face conversa-

[10]https://rapidtyping.com/typing-tutor-freeware.html

tions.

- If you noticed the audio during your object interactions, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?
- If you noticed the audio during your conversations, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?
- If you noticed the window panels during your object interactions, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?
- If you noticed the window panels during your conversations, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?
- If you noticed the camera feed during your object interactions, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?
- If you noticed the camera feed during your conversations, did the experience make you feel comfortable? (Likert-based range -3 to +3). Any comments?

Non-VR User Preferences: For the evaluation of the impact of the Emotion Display regarding the face-to-face conversations with the VR user, we will use our custom question:

- When using the virtual eyes on the from of the VR helmet in your conversations, did the appearance of the eyes make you feel comfortable? (Likert-based range -3 to +3). Any comments?

5.2.4 Experimental Procedure

Before entering the research venue, the participants will be screened for sickness symptoms and will only proceed if in good health. We will then assign pairs, with one partner (Subject A) as the VR user and the other (Subject B) as the non-VR user/colleague.

Their roles will swap in their second session. Then, Subject A will have an introduction session and sign the consent form. After the consent form, there will be a pre-experiment CVSQ and a typing exercise (10 minutes) on a PC desktop to obtain baseline desktop typing performance (Figure 5.6.1). In the meantime, we will explain the task to Subject B with their scripted dialogues.

For the next step, Subject A will go to a training phase to briefly practice the tasks and experimental flow. The tasks include a working task (keyboard typing), a relaxation task (watching a movie), and having a conversation with Subject B. When the training phase finishes, Subject A will move into the actual experiment phase with the same sequence of tasks: keyboard typing (10 minutes), movie watching for 10 minutes (see Fig. 5.6.2), and a conversation (see Fig. 5.6.3). During this VR time, Subject A can either use the software interface or voice commands to open the visual channels at any time for the convenience of using the keyboard for typing. We will encourage the subject to close all external visual channels while (s)he watches the movies for enhancing the immersed experience. Note that only one of the two conversations will have the Emotion Display activated and we will counterbalance the order of these activations. After the two cycles of tasks, Subject A will remove the HMD and move to the PC to answer the UEQ, post-experiment CVSQ, and VR User Preference Questions, and Subject B will answer the Non-VR User Preference Questionnaire on the same PC (see Fig. 5.6.4).

Afterwards, both subjects will come back to the waiting area to arrange an appointment for the second session. Note that in the next (and final) session, the role of the subjects will be swapped and we will give out two vouchers for the participants. The VR user will be required to stay at the lab for a minimum of 15 minutes before leaving the venue and warned not to drive any vehicles for two hours. The experimenter will then perform a hygiene cleaning process for the equipment.

5.3 Discussion

In this chapter, we suggested a possible solution for VR user and colleagues to better interaction and communicate in an office environment using the Workspace-VR HMD system. To evaluate the new Workspace-VR HMD system in terms of user experience and communication satisfaction, we designed a user study from research questions and hypotheses.

Through the user study, we expect that participants will learn to properly handle the system easily and quickly after a detailed training session. We used tasks that are typical in any office environment. We anticipate that, by using Workspace-VR to accomplish those tasks, users will see the advantages of the system and rate our system from "Good" to "Excellent" on the UEQ. In terms of the negativity of visual fatigue during system use, we expect that the health condition of each participant before and after the VR session will show no significant differences. Regarding the user performance in typing, we hope for comparable quality between the PC and VR typing tasks. As we also ask for VR user preference, we look for a comfortable experience with the use of the bone-conduction headset, DI, and VST technologies. In addition, we presume that the VR user will prefer the DI technology for keyboard interactions and VST for conversations over the use of DI for conversations and VST for the object interactions, due to their different view coverage and convenience. Moreover, in the evaluation of the Emotion Display as part of Workspace-VR, we hope to see that most non-VR participants report that the use of the Emotion Display helps provide a degree of social connection with the VR user through eye contact.

5.4 Expected Future Work

Some features should be enhanced or added to make the Workspace-VR system more comfortable and more natural. Firstly, the system should be able to capture and deliver more of the user's emotions, such as analyzing the voice and tone during a conversation or enabling the user to express/select their desired emotion to display, as well as enhancing the realism of the digital eyes. Furthermore, to provide a better visual experience for the VST technology, there is a need for a higher resolution and even additional depth information for the front camera.

Regarding the design of the 3D printing cowl, it is necessary to optimize the design with a slight reduction in the size of the LCD window panels to increase the field of view in VR, as well as having two more left- and right-side LCD panels (like in the original DI work).In addition, we would like to darken the LCD panels by adding polarizer film layers to provide a higher level of immersive light blocking. Finally, for providing more options for the non-VR participant to initiate a conversation with the VR person, instead of only depending on the sound signal (colleague calling), we can install a camera in front that captures the RW view behind the VR user. With this, the non-VR user would be able to approach from behind and wave to the camera to let the system inform the VR user of their presence.

Many other options exist, and can be supported using our scalable Client-Server architecture. Since each Client can connect and control various aspects of the DI technologies, independent of what application the VR user is accessing, there is a wide range of possibilities that we hope to explore in the future.

5.5 Chapter Summary

In this chapter, we described our Workspace-VR HMD system (based on the HTC Vive platform) as an advanced device, built on the learnings from the MDI HMD described in Chapter 4, for VR users to overcome typical visual/audio isolation. This HMD system supports the VR user accomplish important physical-world interactions, e.g., with nearby objects and people, and also for the non-VR users to engage in more natural conversations with people wearing immersive VR HMDs. Workspace-VR combines visual (DI providing peripheral view area, VST providing front and centre view region) and auditory (HTAR) channels, and an Emotion Display virtual eye pair. We also designed a complete user study in an attempt to target research questions 2 (How can we ease RW interactions for VR users (including nearby objects)?) and 3 (How can we facilitate face-to-face conversations between VR and non-VR users?). We expect the design will stimulate conversations about how to better integrate VR and non-VR users into office settings in the future. Although we could not conduct an actual experiment to verify our hypotheses, or to confirm answers to the research questions, we managed to submit part of the work to a VR conference venue and planned a full user study to be conducted when circumstances permit.

In the next chapter, we make a summation of the achieved work regarding the research questions with overall conclusions, academic contributions, and further future work.

Chapter 6

Conclusions, Contributions, and Future Work

6.1 Conclusions

The author explored the research topic of providing and evaluating solutions and techniques to support office users engaged in prolonged VR use. There are fundamental health-related problems for a VR user in adjusting to being in a virtual environment for long periods of time, maintaining comfort within it and readjusting back to the RW afterwards, and practical difficulties when needing to interact with the physical world, including reaching nearby items and having natural conversations with colleagues. The author then specified the research questions along with the thesis road-map to tackle those problems, and reviewed the literature of existing works on these issues. This background information was used to help construct potential solutions and techniques to mitigate the negative effects, enable the VR user to operate the HMD without having to leave it, and switch seamlessly between the VR and the physical worlds. These solutions need additional usability testing to evaluate the proposed solutions, and if successful, integration into common VR uses and contexts.This will require both technical and systematic adaptation into a unified HMD system for long-duration VR usage.

Aiming for a healthy VR experience (answering RQ 1), a health recovery regimen was proposed for VR users to perform in between VR sessions, and also post-VR, before leaving VR and returning back to the RW. The technique of Active Breaks was brought from tried-and-true clinical contexts into VR to target visual problems and possible relevant sickness. The purpose was to provide the user with a high level of visual health through hours of working with a VR device, and can be applied to mid-session breaks, or before the user reenters the RW. We designed and conducted a user study to evaluate the impact of the Active Breaks technique. Our results showed that users preferred the use of Active Breaks compared to a no-practice VR experience (the norm today). The RW version showed promising usage and recovery capabilities in terms of recovery speed and efficiency, but needs a more in-depth evaluation to assess its true potential. The VR version of a thumb-moving reorientation technique was not found to be as effective for users of conventional HMDs as a figure-eight exercise, which could be usable in the VR context. Subjects did give the Active Breaks techniques high rates of approval, however.

To achieve a continuous and immersive workflow within a VR HMD while also being able to reach out to the physical workspace to do essential RW tasks (RQ 2), the author developed an MDI HMD. This headset was a simple integration of technologies including VST (for centre visual view) and DI (for peripheral visual view) using a simple Arduino controller. This HMD allowed the user to absorb the RW visually while staying in a VR office space. The user could see the RW from both the camera plane and LCD panels by pressing a button. We then designed and conducted a usability test for the new HMD. The results showed that users preferred to use the MDI HMD, and further, the combination of the two used technologies worked well with different tasks. However, the MDI HMD still had limitations with the fish-eye lens camera placement and usage, uncontrollable drifting of the VE, and an issue of nose bridge blocking. These limitations needed technical optimisations integrated with a more stable/robust platform and more advanced features to support different users, which we added in our subsequent contribution.

Consequently, we decided to move the implementation of the technology integration (DI, VST) from the MDI HMD using a smartphone to an HTC Vive HMD. The intention was to tackle both RQ 2 (How can we ease RW interactions for VR users (including nearby objects)?) and RQ 3 (How can we facilitate face-to-face conversations between VR and non-VR users?) in one HMD system. This new HMD was designed with a 3D printed part to better incorporate the DI technology components, and used the built-in camera from the HTC Vive for the VST visual channel. A sophisticated and scalable Client-Server software model was used to make the system extendable in terms of management from a single user to multiple HMDs with multiple clients access it at a time. In addition, a simple Emotion Display component was also designed and implemented, along with the use of audio HTAR technology, using a bone-conduction headset, for supporting the sense of ambient sound and a natural conversation for both the VR and non-VR user. We then designed a user study for evaluating the system. Although there was no face-to-face user study performed due to social distancing requirements at the time, the author was able to submit part of the work to a conference, and plans to run the user study when social distancing laws are relaxed.

As a result, the author expects the work and attained knowledge will contribute to enhancing the experience of prolonged VR usage, especially in office environments. It is acknowledged that valuable insights gained during the development and evaluation process have triggered new questions and suggest room for improvements. These will be presented in the last section in our discussion on Future Work.

6.2 Contributions

In terms of contributions, the author discussed problems related to office users wanting to use VR in their workplace over a long period (for instance, a typical nine-to-five workday) including VR sickness and access to RW objects, and workplace interactions between both VR and non-VR users. The problems corresponded to three key research questions. To address the issues, the author proposed a novel health recovery technique (Chapter 3) and new HMDs, advancing from MDI HMDs in Chapter 4 to a Workspace-

VR HMD system in Chapter 5) as apparatus-based solutions. Then the author designed usability tests (reviewed and approved by the University's Human Ethics Committee) to evaluate the proposed solutions in different aspects regarding the user's health and experience. In line with the research, the author published two papers in peer-reviewed conferences, and submitted a third for another major conference.

- Tran, K. T. P., Jung, S., & Lindeman, R. W. (2020). "On the use of "Active Breaks" to perform Eye Exercises for more Comfortable VR Experiences". In IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (2nd Annual Workshop on Immersive Sickness Prevention) (pp. 468–476). Atlanta, USA: Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/VRW50115.2020.00096.

- Tran, K. T. P., Jung, S., Hoermann, S., & Lindeman, R. W. (2019). "MDI: A Multi-channel Dynamic Immersion Headset for Seamless Switching between Virtual and Real World Activities". In 26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings (pp. 350–358). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/VR.2019.8798240.

This work suggests some important advice for developers:

Visual Health Recovery: Active Breaks might be a good visual health recovery technique. First, the technique provides natural manner for focal and muscle training for the user's eyes for a rapid reduction of visual fatigue caused by VAC. Second, Active Breaks can be performed quickly during breaks from VR or before the person returns to the RW.

Real-world Object Interactions: Our system provides visual channels with a wide field of view, and the transition between the two worlds is smooth, not requiring the user to remove the HMD. Specifically for the visual channel, VST technology provides a higher sense of presence than DI. In addition, the bottom LCD panels of

DI need proper placement for the eyes to fuse what they see. However, DI offers high naturalness in viewing the RW over VST, and has no resolution or delay constraints. Finally, looking out to the RW using DI's LCD panels may have the potential to reduce VR sickness, due to seeing RW grounding cues.

VR and Non-VR Communication: Concerning the asymmetric communication between a VR user and a non-VR colleague, there are three findings. First, the integration of an artificial eye contact cue, for instance, the Emotion Display, may help the non-VR person feel more engaged in the conversation. Second, the VR person can choose bone-conduction headphones or high-end noise-cancelling headphones to receive RW audio cues. The first option directly and naturally provides ambient sound, while the noise-cancelling headphones allows the developer to blend the ambient and computer-generated sound at any desired level. Third, VST technology is a good candidate for the visual channel due to its capability of capturing the view in front of the VR user.

6.3 Future Work

Along the development and evaluation process, we obtained valuable insights which suggest room for improvements and extensions in terms of engineering and evaluation (see Fig. 6.1).

- The front camera of the system should be of higher resolution than either the fish-eye or the HTC Vive Pre camera. This would provide a better experience, and might even include depth information to create a more immersive experience for the user. Moreover, the software interface should be adjustable to see-through and overlay on the video feed to utilize the display area of the front captures better.
- The cowl should be designed in a form that reduces the distance from the face to the lenses. Then a smaller pair of the bottom LCD could be used and would

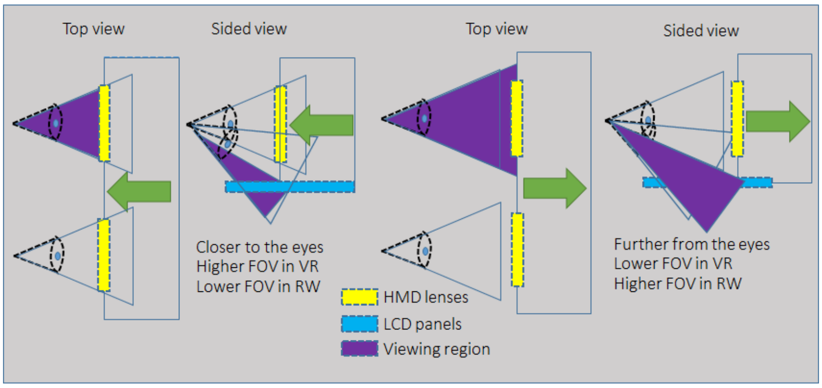

Figure 6.1: The proposed design approach for a more adaptive HMD where the lenses and display structure of the HMD can move back and forth to increase or reduce the FOV of the LCD panels windows for better RW viewing or better VR viewing experience.

provide a greater FOV for the VR user than the current Workspace-VR HMD version.

- A more advanced feature would be making the cowl movable with the rest of the HMD lens structure. Thus, the user or system could decide the degree of FOV reduction/wideness of the LCD panels.

- The LCD panels could be made to become more opaque for greater immersion experience by applying additional polariser films, or other technology.

- One camera with face recognition could be placed in front of the user to capture the view behind. The application could then tell the VR user when a person was approaching. A signal could then be sent to the VR user, who could take appropriate preparation and action.

- The Mic-through AR (MTAR) audio technology, for instance a noise-cancelling headset, could be used to give the VR user more control in selecting their preferred source of sound (ambient or CG) and how much sound should be produced. This provision could be made consistent with a visual cue, where the user would select the level from a semi- or fully-immersive experience while using the MTAR for the sound channel. Currently, users can only achieve semi-immersive (audio) settings from bone-conduction headphones. Note that both visual and audio channels are already provided with both RW and augmented information.

Thus, a comparison of MTAR and HTAR from the user point of view will bring valuable understanding for multi-sensory experience design.

Aside from the above improvements for the system, we anticipate more research questions such as the possibilities below, and offer possible attack strategies.

1. **How can we more deeply evaluate the RW version of Active Breaks to establish its significantly positive impact on VR users?** There is a need for a user study to assess the visual health recovery technique, particularly in the RW context, in terms of efficiency, body reaction, and recovery time and duration. The VR user could experience a normal VR session and then do the exercises. The visual health of the user could be measured with objective measurements for heart rate using reliable devices and visual tests, supported by subjective questionnaires.

2. **Can DI technology, with its natural view of the RW, contribute to reducing visual fatigue and VR sickness?** Looking through LCD panels seems to be natural, and we believe in the potential of these displays for the reduction of VAC and vection. To evaluate the potential, we could design a user study with subjective VR sickness and visual fatigue questionnaires and objective measurement devices to measure the user's visual health objectively. Since it has been shown that providing a reference frame can reduce VR sickness [30,31,89,133], it should follow that imperceptibly opening the windows should provide some relief. For the study, the visual stimuli could be some motion-induced games or applications in the VR, allowing the user to open the windows when they feel discomfort. We could then compare this with taking off the HMD, and the normal condition, where there is no remedy.

3. **How can we make the Emotion Display more intelligent, dynamic, and realistic to benefit both the VR and non-VR user?** For instance, a microphone could be used to capture the voice of the VR user, and if it catches emotional keywords, it could correspondingly alter the visual display of the virtual eyes.

Alternatively, an explicit way of specifying "eyemojis" could be designed, allowing the VR user to display and change them on demand. In addition, the eye-pairs could be replaced with high-resolution displays to show more-realistic eyes, and an the eye-tracking device could provide digital eyeballs with gazing behaviour following the user's actual eye movements. A development such as this would be accompanied by user experience monitoring and surveys.

4. **What effect would adding more LCD panels for peripheral RW viewing have on the user experience, and what applications/scenarios would benefit from this?** We could design another version of the Workspace-VR HMD with a new 3D-printed cowl and survey the user preference on the presence of the additional windows. This could be tried with HMDs from other manufacturers as well, in order to expand the accessibility of MDI.

5. **How well would the Workspace-VR framework work for actual long-term immersion?** A user study with 8-12 hour sessions over multiple days should be conducted to assess the level of sickness and other problems, and elicit user comments and feedback on the experience to assess longer-term implications. In this setting, we would investigate the efficiency of Active Breaks, the efficiency of and preference for the various visual channels, audio-channel preferences, and the feeling of engagement and overall usability for users in a prolonged VR usage scenarios.

From these questions, it is clear that this exploration of ways of supporting and improving long-duration immersion in real contexts has only scratched the surface of this important research area within VR. Indeed, if VR is to have the deep and wide-spread impact and usage proclaimed by many, future work in this fertile area of research will lead to profound contributions.

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Appendix A

HIT Lab NZ
Telephone: +64 3 369-2226
Email: Kien.TranPhamThai@pg.canterbury.ac.nz
03/07/2019

Toward healthy VR experiences: Can performing eye exercises reduce visual stress for immersive VR users?

I am Kien, Tran Pham Thai, a PhD student at HIT Lab NZ, University of Canterbury. I am conducting this experiment to evaluate the efficacy of having eye-recovering exercises for virtual reality (VR) user and its impacts on eyestrain, which is caused by a long immersive time in a head-mounted display (HMD).

In the clinic, people with eye stress symptoms or who have difficulty seeing, are recommended to perform exercises such as finger moving, and/or figure 8. These practices recover their eyes back to the normal stage, efficiently and rapidly. In VR, people also experience visual disturbances, and one standout problem is eyestrain. This phenomenal caused mainly from Vergence-Accommodation-Conflict (VAC, unusual eye stage in virtual environment, when using conventional HMD). The idea of this work is to allow VR users to practice the same exercises as in the clinic with or without wearing VR HMD. In one condition, the user can carry out the two exercises in the real world (RW exercises condition) by taking off the HMD. In the other condition, the user will wear the HMD while doing similar exercises, but in a virtual environment, (VR exercises condition). We hope these exercises will have a positive impact on the reduction of eyestrain, and the exercises can achieve similar or equal efficiency of the RW ones, and keeping the users in their most immersive.

If you choose to take part in this study, your involvement in this project will be:

- You will start with an introductory session (5 min) to understand the purpose of the experiment, devices and controls, settings, tasks, right of cancellation, potential risks and procedure, recommendations for safety, and filling in and sign the consent form. You will need to focus also on the content of the videos and give feedback at the end of each condition.
- After completing the consent form, the researcher will ask you to fill in a pre-experimental questionnaire and screening questionnaire.
- Your eye movement will be captured by the headset, which you will wear. You will watch two 360-degree videos in VR. After a while, there will be a message from the movie asking you to pause the video and start two eye-exercises in the real world [or in VR]. When you finish the exercises, you will put back on the headset [resume the video] and continue watching until the next message show up.
- You need to do headset adjustment (IPD, positioning) to achieve comfort and clear view in VR before starting the condition.
- If you start with exercise-based conditions, the researcher will train you with exercise concepts and techniques (thumb moving and figure 8) and the implementations of those in VR and RW settings.
- You will watch a first 30 min 360-degree video.

- You will keep watching the movie until a message tells you to pause the VR movie and start doing exercises. Then you do the exercises as trained, depending on the VR or RW condition, and each exercise lasts for around 1 minute. When you are finished, you will go back to VR, continue watching the movie until the next instruction arrives.
- After finishing the condition, you will fill in questionnaires; give comments on the absorbed content in 5 minutes.
- You will then do the last condition of the experiment in 35 minutes.
- After you are done with both conditions in each group, you will answer the same questionnaires plus giving a short comment about your overall experience.
- At the end, an appreciation form and a $15 voucher will be given to you as compensation for your time.
- **You should not drive or operate any heavy machines within two hours after this experiment.**

While performing VR tasks, there is a risk of feeling nauseous or cybersickness. Depending on the levels of severity, you can wait until the end of each condition to have a break if your unpleasant symptoms are insignificant. If you feel it is difficult for you to continue, you can sit down and relax on the couch until you feel comfortable. In the worst-case scenario, if you cannot perform at all or you have unforeseen behavior, the researcher will terminate your experimental session and escort you to the UC Health Centre. However, the likelihood of this to happen is very small. In the case of having an unpleasant experience, you can decide to stop and leave this experiment at any point in time.

Participation in this study is voluntary and you have the right to withdraw at any stage without penalty. You will still receive the compensation if you cannot continue. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of the raw data starts on 01/09/2019, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, names will not be recorded, anonymous identifiers will be used instead. Data will be protected by password and deleted after 10 years. The access rights are only granted to the research team. A research thesis is a public document and will be available through the UC Library. However, it will not contain identifying information.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out as a requirement for a PhD degree by Kien, Tran Pham Thai under the supervision of Prof Robert W. Lindeman, and Dr Sungchul Jung who can be contacted at gogo@hitlabnz.org., and sungchul.jung@canterbury.ac.nz respectively. They will be pleased to discuss any concerns you may have about participation in the project.

This project has been reviewed and approved by the University of Canterbury Human Ethics Committee, and participants should address any complaints to The Chair, Human Ethics Committee, University of Canterbury, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz).

If you agree to participate in the study, you are asked to complete the consent form and return it to the experimenter.

HIT Lab NZ
Telephone: +64 3 369-2226
Email: Kien.TranPhamThai@pg.canterbury.ac.nz
03/07/2019

Toward healthy VR experiences: Can performing eye exercises reduce visual stress for immersive VR users?

Include a statement regarding each of the following:

- ☐ I have been given a full explanation of this project and have had the opportunity to ask questions.
- ☐ I understand what is required of me if I agree to take part in the research.
- ☐ I understand that participation is voluntary and I may withdraw at any time without penalty. Withdrawal of participation will also include the withdrawal of any information I have provided should this remain practically achievable.
- ☐ I understand that any information or opinions I provide will be kept confidential to the researcher, Prof. Rob Lindeman, and Dr. Sungchul Jung and that any published or reported results will not identify the participants. I understand that a thesis is a public document and will be available through the UC Library.
- ☐ I understand that all data collected for the study will be kept in locked and secure facilities and/or in password protected electronic form and will be destroyed after ten years.
- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Kien, Tran Pham Thai (Kien.TranPhamThai@pg.canterbury.ac.nz), supervisor Prof. Rob Lindeman (gogo@hitlabnz.org), or Sungchul Jung (Sungchul.jung@canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
- ☐ I would like a summary of the results of the project.
- ☐ By signing below, I agree to participate in this research project.

Name:______________________________Signed:____________________________Date:________________

Email address *(for report of findings, if applicable)*:____

Please return this form to the experimenter.

Appendix B

HIT Lab NZ
Telephone: +64 3 369-2226
Email: Kien.TranPhamThai@pg.canterbury.ac.nz
17/07/2018

MDI: A User Study for Multi-channel Dynamic Immersion Headset for An Effective Interaction with Real World.

I am Kien, Tran Pham Thai, a PhD student at HIT Lab NZ, University of Canterbury. One of the goals of Virtual Reality (VR) is providing a fully immersive virtual experience to the user. I am conducting this experiment to test the usability of a new type of VR headset (called a Head-Mounted Display or HMD).

To achieve a higher level of immersion, the human vision system has to be dominated by a computer-generated digital image. To improve immersion, researchers have adopted two approaches: a VR Cave-like system with projectors surrounding the user, or HMD based VR. However, researchers discovered negative effects of current HMDs due to the lack of cues from outside of HMDs while participants are wearing headsets. This also causes problems in carrying our simple actions, such as sensing and manipulating nearby items such as the keyboard or a water mug. Mental frustration caused by these limitations, leading users to feel like they have to break their VR session by taking off the headset to do these very simple actions.

To address these problems, we propose a new HMD design. In this experiment, we will compare several HMD designs in practical scenarios where you will carry out both VR tasks and real-world interactive tasks to evaluate usability.

If you choose to take part in this study, your involvement in this project will be:

- You will start with an introductory session (5 min) to get an understanding about the purpose of the experiment, devices and controls, objects and settings, tasks, a right of cancellation, camera recording purposes, potential risks and procedures, recommendation for safety, and filling in and sign the consent form.
- After completing the consent forms, the researcher will hand out a set of pre-experiment questionnaires for you to fill in.
- After that, you will complete some tasks using each of the four devices we are comparing. In each condition, you will go through the following steps:
    - A brief training session (2 min).
    - Real tasks (10 min), including the main VR task of typing text sentences, and three interactive tasks (in a randomised order) of moving a water mug from one position to another, answering a phone call and writing down information using a sticky note and a pen, and replying to text messages.
    - Filling in questionnaires (5 min).
    - After each condition, there will be a 1-2 minute break.

    - After the last condition, there will be a post-experiment questionnaire to survey your preference for the devices.
- In the end, an appreciation form and vouchers will be given to you as compensation for your time.
- **You should not drive or operate any heavy machines within two hours after this experiment.**

While performing VR tasks, there is a risk of feeling nauseous or cybersickness. Depending on the levels of severity, you can wait until the end of each condition to have a break if your unpleasant symptoms are insignificant. If you feel it is difficult for you to continue, you can sit down and relax on the couch until you feel comfortable enough. In the worst-case scenario, when you cannot keep performing at all or having unforeseen behaviour, the researcher will terminate your experimental session and escort you to UC Health Centre. However, the likelihood of this to happen is very small. In case of having an unpleasant experience at any level, you can decide to stop and leave this experiment at any point in time.

Participation in this study is voluntary and you have the right to withdraw at any stage without penalty. You will still receive the compensation if you cannot continue. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of the raw data starts on 01/09/2018, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, names will not be recorded, anonymous identifiers will be used instead. Data will be protected by password and deleted after 10 years. The access rights are only granted to the research team. A research thesis is a public document and will be available through the UC Library. However, it will not contain identifying information.

Please indicate to the researcher on the consent form if you would like to receive a copy of the summary of results of the project.

The project is being carried out as a requirement for a PhD degree by Kien, Tran Pham Thai under the supervision of Prof Robert W. Lindeman, and Dr Sungchul Jung who can be contacted at gogo@hitlabnz.org., and sungchul.jung@canterbury.ac.nz respectively. They will be pleased to discuss any concerns you may have about participation in the project.

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17/07/2018

MDI: A User Study for Multi-channel Dynamic Immersion Headset for Effective Interaction with Real World.

Include a statement regarding each of the following:

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- ☐ I understand the risks associated with taking part and how they will be managed.
- ☐ I understand that I can contact the researcher Kien, Tran Pham Thai (Kien.TranPhamThai@pg.canterbury.ac.nz), supervisor Prof. Rob Lindeman (gogo@hitlabnz.org), or Sungchul Jung (Sungchul.jung@canterbury.ac.nz) for further information. If I have any complaints, I can contact the Chair of the University of Canterbury Human Ethics Committee, Private Bag 4800, Christchurch (human-ethics@canterbury.ac.nz)
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- ☐ By signing below, I agree to participate in this research project.

Name:__________________________ Signed:________________________ Date:______________

Email address *(for report of findings, if applicable)*:____

Please return this form to the experimenter.

Appendix C

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HIT Lab NZ
Telephone: +64 3 369-2226
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03/07/2019

Workspace-VR: Utilize VR HMD to support long VR session usage

I am Kien, Tran Pham Thai, a PhD student at HIT Lab NZ, University of Canterbury. I am conducting this experiment to evaluate the efficacy of new solution set, Workspace-VR, in terms of supporting comfort in long term seated virtual reality (VR) setting.

According to one vision for the virtual reality (VR) office, VR should allow us to work productively everywhere, using traditional interfaces and immersive VR headsets (head-mounted displays (HMDs)). Hence, the working environment should be highly customizable to support the user's creativity. However, the article also mentions the limitations of current VR technology for application to offices as situational awareness and entering text using keyboards. The user in VR has no physical situational awareness and is physically isolated. This missing awareness of the surrounding environment happens because the VR user wears an immersive HMD, blocking out the real world, and works in a virtual space. This creates a sense in the VR user of a lack of feeling of being with other people around, as well as awkwardness for other people who might want to talk to the VR user. Besides this, interactions with the physical world such as the keyboard, personal items on the table (mug, smartphone, notebook, pen) using simple actions for a typical workstation become challenges for immersed VR users.

In this work, we propose Workspace-VR as a solution for providing comfort for long-term VR experiences and effective communication methods to the near-field object and colleagues without leaving the HMD. The aim is to equip the user with the capability of doing typical interactions with surrounding objects, as well as having conversations with colleagues without having to take off the HMD. This system is developed upon the commercial HMD, Vive Pre platform, and uses VR desktop application (BigscreenVR) with additional features such as visual channels, noise-canceling headphones (audio channel), emoji display for ease of interaction with nearby objects (keyboard, mouse, cup, smartphone), and communications with other colleagues, correspondingly. In Workspace VR, we implemented two visual channels of video see-through for front view, and dynamic immersion for peripheral view capturing. The video see-through (VST) uses the built-in camera on the Vive to capture the real world (RW), process it, and blend it with the virtual environment. Dynamic immersion (DI) technology is the implementation of transparency-controllable-LCD panels in the periphery area of an HMD. DI allows the user to look through these windows to perceive the RW. To support the engagement in communication between a person and the HMD-wearing person, we propose an emoji display. We rendered the emoji display panel with cartoon-style eyes when a person is having a conversation with the VR user, to give more intimacy.

If you choose to take part in this study, your involvement in this project will be:

- If you are in 1st group:
    - You start with an introductory session (5 min) to understand the purpose of the experiment, devices and controls, settings, tasks, right of cancellation, potential risks and procedure, recommendations for safety, and filling in and sign the consent form.
    - Then you need to answer demographics, CISS screening, SSQ, and CVSQ questionnaires.
    - In the next step, you learn how to use our Workspace-VR from a demo and trial run. For this stage, we also show you how to wear the HMD properly, set IPD value, positioning the HMD to obtain the best visual experience.
    - Then you do a mandatory keyboard typing exercise for 15 minutes.
    - When there is a potential conversation, you use Workspace-VR to react to the person, chat, and see him/her from a camera.
    - When the conversation is over (approximately 2 minutes), you go back to use VR desktop and you have 10 minutes of free activities such as gaming or watching movies.
    - After 10 minutes, you need to do the typing task again for 15 minutes.
    - When the partner coming again, you chat with the person for 5 minutes.
    - You do last 10 minutes of free activities
    - You then answer UEQ, SSQ, CVSQ, IPQ, communication satisfactory questionnaires.
    - Lastly, you have a break for 15 minutes.
    - Before leaving the venue, please take note of the next appointment if this is your first session. We only give out the voucher in the 2nd time of participation.
- If you are in 2nd Group:
    - You need to fill and sign the consent form.
    - You receive a task brief, and study conversation scripts.
    - Then you approach a VR user to initiate a conversation based on what you have learned.
    - After finishing the conversation, you come back to your initial position, wait for 25 minutes.
    - After waiting, you come back to the VR user again with the next conversation.
    - Before leaving the venue, please take note of the next appointment if this is your first session. We only give out the voucher in the 2nd time of participation.
- After you had done both sessions, an appreciation form and vouchers will be given to you as a compensation for your time.
- You should not drive or operate any heavy machines within two hours after this experiment.

While performing VR tasks, there is a risk of feeling nauseous or cybersickness. Depending on the levels of severity, you can wait until the end of each condition to have a break if your unpleasant symptoms are insignificant. If you feel it is difficult for you to continue, you can sit down and relax on the couch until you feel comfortable. In the worst-case scenario, if you cannot perform at all or you have unforeseen behavior, the researcher will terminate your experimental session and escort you to the UC Health Centre. However, the likelihood of this to happen is very small. In the case of having an unpleasant experience, you can decide to stop and leave this experiment at any point in time.

Participation in this study is voluntary and you have the right to withdraw at any stage without penalty. You will still receive the compensation if you cannot continue. You may ask for your raw data to be returned to you or destroyed at any point. If you withdraw, I will remove information relating to you. However, once analysis of the raw data starts on 01/04/2020, it will become increasingly difficult to remove the influence of your data on the results.

The results of the project may be published, but you may be assured of the complete confidentiality of data gathered in this investigation: your identity will not be made public without your prior consent. To ensure anonymity and confidentiality, names will not be recorded, anonymous identifiers will be used instead. Data will be protected by password and deleted after 10 years. The access rights are only granted to the research team. A research thesis is a public document and will be available through the UC Library. However, it will not contain identifying information.

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03/07/2019

Workspace-VR: Utilize VR HMD to support long VR session usage

Include a statement regarding each of the following:

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- ☐ I understand what is required of me if I agree to take part in the research.
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Name:____________________________Signed:__________________________Date:________________

Email address *(for report of findings, if applicable)*:_

____

Please return this form to the experimenter.

Appendix D

Participant number#__________

Pre-Experiment Questionnaire

1. Age:
2. Gender:
    - o Male
    - o Female
    - o Other
    - o Do not wish to disclose
3. Have you used a VR headset before?
    - o Never
    - o Few times per year
    - o Few times per week
    - o Daily
4. Have you experienced any severe VR sickness symptoms when using the VR headset?
    - o Yes
    - o No
5. Do you have normal or corrected-to-normal vision?
    - o Yes
    - o No
6. Do you wear glasses or contact lenses?
    - o Yes
    - o No

Participant number#__________

Convergence Insufficiency Symptom Survey (CISS) questionnaire

Symptom	Never		Infrequently		Sometimes		Fairly Often		Always	
	CI	NBV	CI	NBV	CI	NBV	CI	NBV	CI	NBV
1. Do your eyes feel tired when reading or doing close work?										
2. Do your eyes feel uncomfortable when reading or doing close work?										
3. Do you have headaches when reading or doing close work?										
4. Do you feel sleepy when reading or doing close work?										
5. Do you lose concentration when reading or doing close work?										
6. Do you have trouble remembering what you have read?										
7. Do you have double vision when reading or doing close work?										
8. Do you see the words move, jump, swim or appear to float on the page when reading or doing close work?										
9. Do you feel like you read slowly?										
10. Do your eyes ever hurt when reading or doing close work?										
11. Do your eyes ever feel sore when reading or doing close work?										
12. Do you feel a "pulling" feeling around your eyes when reading or doing close work?										
13. Do you notice the words blurring or coming in and out of focus when reading or doing close work?										
14. Do you lose your place while reading or doing close work?										
15. Do you have to re-read the same line of words when reading?										

Participant number#__________

Computer Vision Syndrome Questionnaire (CVS-Q)

	Frequency			Intensity	
	Never	Occasionally	Often or Always	Moderate	Intense
Burning	○	○	○	○	○
Itching	○	○	○	○	○
Feeling of a foreign body	○	○	○	○	○
Tearing	○	○	○	○	○
Excessive blinking	○	○	○	○	○
Eye redness	○	○	○	○	○
Eye pain	○	○	○	○	○
Heavy eyelids	○	○	○	○	○
Dryness	○	○	○	○	○
Blurred vision	○	○	○	○	○
Double vision	○	○	○	○	○
Difficulty focusing for near	○	○	○	○	○
Increased sensitivity to light	○	○	○	○	○
Coloured halos around objects	○	○	○	○	○
Feeling that sight is worsening	○	○	○	○	○
Headache	○	○	○	○	○

Participant number#__________

Simulator Sickness Questionnaire

Instructions: Circle how much each symptom below is affecting you **right now**.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. Fullness of the Head	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. Vertigo**	None	Slight	Moderate	Severe
15. Stomach awareness***	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort, which is just short.

Participant number#___________

IPQ Questionnaire

Please indicate, whether or not each statement applies to your experience. You can use the whole range of answers. There are no right or wrong answers; only your opinion counts.

You will notice that some questions are very similar to each other. This is necessary for statistical reasons.

Please answer all question with reference to the VR session you just completed.

In the computer generated world, I had a sense of "being there".

not at all ○ ○ ○ ○ ○ ○ ○ very much

Somehow I felt that the virtual world surrounded me.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

I felt like I was just perceiving pictures.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

I <u>did not</u> feel present in the virtual space.

did not feel present ○ ○ ○ ○ ○ ○ ○ felt present

I had a sense of acting in the virtual space, rather than operating something from outside.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

I felt present in the virtual space.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

How aware were you of the real world surrounding while navigating in the virtual world? (i.e., sounds, room temperature, other people, etc.)?

extremely aware ○ ○ ○ ○ ○ ○ ○ not aware at all

I was not aware of my real environment.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

I still paid attention to the real environment.

fully disagree ○ ○ ○ ○ ○ ○ ○ fully agree

I was completely captivated by the virtual world.

fully disagree | ○ ○ ○ ○ ○ ○ ○ | fully agree

How real did the virtual world seem to you?

completely real | ○ ○ ○ ○ ○ ○ ○ | not real at all

How much did your experience in the virtual environment seem consistent with your real world experience ?

not consistent | ○ ○ ○ ○ ○ ○ ○ | very consistent

How real did the virtual world seem to you?

about as real as an imagined world | ○ ○ ○ ○ ○ ○ ○ | indistinguishable from the real world

The virtual world seemed more realistic than the real world.

fully disagree | ○ ○ ○ ○ ○ ○ ○ | fully agree

Participant number#__________

NASA-TLX Mental Workload Rating Scale

Please place an "X" along each scale at the point that best indicates your experience with the display configuration.

Mental Demand: How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc)? Was the mission easy or demanding, simple or complex, exacting or forgiving?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Physical Demand: How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the mission easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Temporal Demand: How much time pressure did you feel due to the rate or pace at which the mission occurred? Was the pace slow and leisurely or rapid and frantic?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Performance: How successful do you think you were in accomplishing the goals of the mission? How satisfied were you with your performance in accomplishing these goals?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Frustration: How discouraged, stressed, irritated, and annoyed versus gratified, relaxed, content, and complacent did you feel during your mission?

Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Comments: Please comment on your experience

Participant number#__________

Post-Experiment Questionnaire

1. Which type of VR headset was easier to use?
    - Original HMD
    - DI HMD (One with only LCD panels)
    - Video-see-through HMD (One with only mounted-camera)
    - MDI HMD (One with both LCD panels and mounted-camera)
2. Which one do you prefer to use?
    - Original HMD
    - DI HMD (One with only LCD panels)
    - Video-see-through HMD (One with only mounted-camera)
    - MDI HMD (One with both LCD panels and mounted-camera)

Participant number#__________

User Experience Questionnaire (UEQ)

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26